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Nationwide Urban Runoff Program Pollutant Removal Capability of Urban Best Management Practices in the Washington Metropolitan Area

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POLLUTANT REMOVAL CAPABILITY of URBAN BEST MANAGEMENT PRACTICES in THE WASHINGTON METROPOLITAN AREA

FINAL REPORT

Submitted by

Metropolitan Washington Council of Governments
Water Resources Planning Board

in association with the

Virginia Polytechnic Institute and State University

and the

Northern Virginia Planning District Commission

October 1983

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Seven area best management practices were monitored and evaluated in terms of their overall pollutant removal performance. The major factors which influenced their effectiveness were identified, and general design principles which would maximize pollutant removal for each type of BMP were proposed.

The types of BMP's evaluated included: "Dry" Stormwater management Ponds, "Wet" Ponds, Grassed Roadside Swale, Infiltration Controls, and Porous Pavement.

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INTRODUCTION

A major component of the Washington area NURP project was an extensive field investigation of the comparative pollutant removal capability of seven urban best management practices (BMPs) in suburban Maryland and Virginia. This chapter details the major findings of this effort and is organized in the following manner. The first section provides a general description of each BMP, and also describes the individual characteristics of each monitoring site. In the second section, the various methods which were used to monitor BMPs and compute their efficiency are discussed. In the third section, each of the urban BMPs are evaluated in terms of their overall pollutant removal performance. Finally, in the last section, the major factors which appeared to influence the effectiveness of each monitored BMP are identified. Based upon this analysis, general design principles that maximize pollutant removal are proposed for each BMP type evaluated.

URBAN BEST MANAGEMENT PRACTICES ANALYZED

Most of the urban BMPs investigated in this study were initially designed and have been extensively applied to control peak discharges of urban stormwater runoff in accordance with local stormwater management criteria. The study was designed to develop field measurements to determine the degree of pollutant removal achieved by these practices and to suggest design criteria which would optimize both peak runoff volume control and also maximize pollutant removal. It was felt that an urban BMP program based upon existing stormwater management regulations and institutions would have the best potential for implementation in the Washington metropolitan area.

Table 1

BMP Monitoring Site Selection Criteria

1. **Tributary Land Use** - BMP sites draining homogeneous land uses were preferred. These land uses had to be typical of those found throughout the Washington metropolitan area. The aggregate of all sites selected should cover the range of land use/site imperviousness/site activity characteristics typically found in the region. Sites having drainage with existing or planned construction activity during the monitoring period were not considered.

2. **Size of Drainage Area** - Sites were preferred which had drainage areas of up to 40 acres for typical "on-site" stormwater management facilities; or which ranged from 50-150 acres for larger "off-site" structures controlling more than one major development.

3. **Soil Types** - Sites were selected to cover the range of predominant soil types and soil hydrologic groupings typically found in the metropolitan area.

4. **Volume of Storage** - Sites were preferred which met or exceeded local jurisdictional stormwater management requirements usually aimed at providing pre-development peak runoff control levels for the two year and/or ten year frequency storm.

5. **Structural Inlets/Outlets** - To minimize equipment installation costs, sampling costs, and data analysis, sites were preferred which had one inlet and/or outlet and a minimum of direct overland flow drainage.

6. **Slopes** - Sites having moderate slopes of 2-7 percent were preferred.

7. **Geographical Coverage** - Sites were selected with the objective of achieving maximum regional coverage in order to provide data which could help determine the transferability of nonpoint loading rates for typical land uses between jurisdictions. Sites were also preferred which were located in watersheds which had been rated as "critical" by the Metropolitan Washington Water Resources Planning Board because of existing or forecasted nonpoint loading problems.

8. **Monitoring Station Access and Security** - Sites which had good regional access under all weather conditions were preferred. Because the laboratory for sample analysis was located outside of the region's central area, it was important for sites to be reasonably proximate to major interjurisdictional transportation routes such as the Washington beltway I-495, I-95, I-270, and I-66. This minimized the time required for sample collection following storm events. Considerations as to overall station security and the susceptibility of monitoring equipment to potential vandalism were also important in site selection.

BMP Site Selection

The site selection process for evaluating the pollutant removal potential of urban BMP's was extensive. Local stormwater technicians from a special Water Resources Planning Board Committee identified and evaluated hundreds of structures in the region as candidates for monitoring under the Washington NURP project. Candidate sites were ranked according to a common set of criteria identified in Table 1. The final set of sites that were evaluated were selected from this list. Complete details of the site selection process can be found in an earlier NURP project report (MWCOG, 1980). A brief discussion of each BMP type evaluated along with the specific monitoring site(s) is presented below:

"Dry" Stormwater Management Ponds

"Dry" stormwater detention ponds are typically designed to temporarily store runoff to attenuate, or "shave", peak runoff rates from developed areas. Such structures have been the single most common stormwater control applied within the Washington area. Over 2000 have been constructed in area jurisdictions since the early 1970's (MWCOG, 1983b). Normally empty during dry weather, these basins rapidly fill up during large storm events. The release rate of water from the basin is controlled by the size of the outlet pipe or control device that drains the pond. Typically, such structures are designed to detain stormwater for one to two hours. The dry pond investigated in the course of this study was located in the Lakeridge subdivision in Prince William County, Virginia. Essential characteristics of the pond are detailed in Table 4.

Extended Detention Dry Ponds

A major question evaluated under the NURP study was the extent to which the runoff detention time in conventional dry stormwater ponds could be modified to enhance their pollutant removal capabilities. Based upon previous local investigations sponsored by the WRPB (NVPDC, 1980), it was thought that modifications to traditional dry pond design which extend detention times would provide time for increased settling and removal of pollutants entrained in urban runoff. To test this hypothesis, a conventional dry pond at the Stedwick site in Montgomery Village, Md. was modified to achieve greater detention times. The original outflow pipe was modified by adding a perforated riser enclosed in a gravel jacket that controlled pond release and drawdown. As a result, stormwater runoff was detained for 6 to 8 hours, instead of the typical one to two hours. It should be noted that the original design of the pond modification called for detention times of up to 24 hours. Unfortunately, the pond outlet modification apparently leaked and never achieved detention times exceeding 8 hours. Principle features of this facility can be found in Table 5.

"Wet" Ponds

Stormwater retention or "wet ponds" represent a small but growing segment of local stormwater structures. In addition to providing temporary storage for peak runoff volumes as in dry ponds, these structures also have additional storage and outlet devices which maintain a permanent pool of water throughout the year. As such, they serve as a multipurpose landscape feature for the developer, providing aesthetic, recreational and wildlife attraction benefits.

An important hypothesis investigated under the Washington NURP project

was that wet ponds also had significant potential to be quite effective in removing pollutants borne in urban runoff. The major reason for this assessment was that several different pollutant removal mechanisms were believed to operate in these ponds, including physical settling, chemical flocculation and transformation, and biological uptake. The three wet ponds which were monitored were Burke, Westleigh and Fair Oaks. Their principal characteristics are detailed in Tables 6 through 8.

Grassed Roadside Swale

Another promising urban best management practice evaluated was the replacement of conventional roadside curb and gutter conveyance systems with grassed swales. Such practices had been applied in suburban areas of Washington as stormwater management structures designed to reduce peak runoff volumes through reduced impervious area and infiltration into the soil profile. Swale drainage systems have usually been applied to control runoff from low density residential areas.

The removal of pollutants in runoff via swales was hypothesized to occur in several ways. First, the grassed swale drainage area would be expected to accumulate airborne and vehicular pollutants at lower rates than commonly experienced with impervious curb and gutter systems because of their smaller degree of impervious cover. Secondly, as stormwaters passed through the grassed swales, it was thought that the vegetation would act as a natural filter, removing pollutants and allowing the runoff to infiltrate into the soil profile where additional pollutant removal might be accomplished. In the NURP study, the quantity and quality of runoff from these grassed swale sites was compared to observed runoff from similar sites utilizing conventional curb and gutter collection systems. The swale sites monitored were at Dufief, Fair Ridge and Stratton Woods. The general features of these sites are elaborated on in Tables 9 through 11

Infiltration Controls

Another emerging concept in Washington area urban stormwater management has been the application of soil infiltration control structures as a means of achieving stormwater management effectiveness. Infiltration controls collect and route runoff into devices which allow for gradual infiltration of the stormwater into the soil profile or through a coarse gravel filter. This serves to provide temporary storage for the stormwater, where pollutant removal can occur by various physical, chemical and biological means. An additional pollutant removal mechanism was assumed to be direct reduction in flow volumes, since some portion of the flow would be permanently directed into the soil profile.

In the NURP study, two infiltration design concepts were investigated. The first involved the use of an infiltration trench in a small community shopping center at Burke Village in Fairfax, Virginia (Table 12). This structure was located adjacent to the center's parking lot, and consisted of a shallow trench backfilled with coarse gravel. The trench was connected with storm drainage system via an outlet pipe at the end of the trench. The total storage associated with the structure was slightly over 11,000 cubic feet, which represents about 1/2 to 1/3 of the volume of runoff expected from the tributary shopping center during the two-year design storm.

The second infiltration device, the Dandridge infiltration pit, was designed to divert runoff from a townhouse development into a gravel pit, which was drained by a series of underground perforated tile drains. The void space within the structure, slightly over 4000 cubic feet, was approximately one half of the storage required to control runoff from the two-year design storm (Table 13).

Porous Pavement

Another urban best management practice which has gained popularity in recent years is the utilization of porous pavement in lieu of normal asphalt in parking lots. These structures are similar in many respects to infiltration controls in that they divert a significant portion of the stormwater runoff volume into the soil profile. In the porous pavement site monitored in the Washington area NURP project (Rockville City Center Parking Lot - Table 14), the stormwater from a 2.2 acre conventional pavement area was conveyed over 2.0 acres of "popcorn" porous pavement. The porous pavement was underlain by a bed of coarse gravel, and drained by a series of perforated tiles that conveyed some of the stormwater to the outlet area. The rapid infiltration of the stormwater through the many pores of the pavement, the subsequent absorption of pollutants to soil particles, and the general downward movement of water to the groundwater pool were hypothesized to control stormwater and effectively remove a wide variety of pollutants.

TABLE 4
BMP FACT SHEET

GENERAL FEATURES

FACILITY NAME: LAKE RIDGE
TYPE OF BMP: Conventional Stormwater Detention Basin (DRY POND)
LOCATION: Thousand Oaks subdivision in Prince William, Virginia

OPERATION: Empty basin fills up with runoff during a storm event, release of water is governed by the size of the outflow pipe, and the height of the riser. Detention within the pond is typically 1-2 hours. Pond was a converted sediment trapping basin.

POLLUTANT REMOVAL MECHANISM(s)

Reliance on physical settling alone and minimum infiltration into the pond bed which occurred during brief peak flow residence times (1-2 hours)

WATERSHED CHARACTERISTICS

DRAINAGE AREA: 88 acres
LAND USE: Townhouse
DENSITY: 6.1 DU/acre

IMPERVIOUSNESS: 31%
EFFECTIVE IMPERVIOUSNESS: 25%
WATERSHED SERVICED BY BMP: 100%
SLOPE: 7.9%
SOILS: Loamy Sediments of the Coastal Plain (@ 70% HG "B")

DESIGN FEATURES

STORAGE VOLUME: 210,000 cubic feet control the 10 year, 2 hour design storm

OTHER CHARACTERISTICS:
- 7.5 foot riser
- poorly vegetated
- formerly a sediment trap
- surface area = 1.2 acre

MONITORING ARRANGEMENT

CHARACTERISTICS: Type "H" flumes at inlet and outlet of pond

STORM EVENTS MONITORED: 28 synoptic storm events between August 1980 and August 1981; 49 inflow events, 41 outflow events.

METHOD(s) USED TO CALCULATE EFFICIENCY

Methods A, B, and C. (For explanation see section in this chapter headed Methods Used Analyzing BMP Removal Efficiencies).

OTHER NOTES

TABLE 5
BMP FACT SHEET

GENERAL FEATURES

FACILITY NAME: STEDWICK
TYPE OF BMP: Extended Detention Dry Stormwater Pond
LOCATION: Montgomery Village, in suburban Montgomery County, Maryland

OPERATION: Stedwick was modified from a conventional peak shaving dry pond to an extended detention facility. The outflow pipe was replaced with a perforated riser enclosed in a gravel jacket. This modification was designed to detain stormwater runoff for up to 24 hours, instead of the 1 to 2 hours typically observed in conventional dry ponds.

POLLUTANT REMOVAL MECHANISM(s)

It was hypothesized that the extended duration of stormwater detention would lead to increased settling of particulate pollutants, and that removal of pollutants via chemical flocculation and transformation also might take place.

WATERSHED CHARACTERISTICS

DRAINAGE AREA: 34 acres
LAND USE: Townhouses
DENSITY: 6.1 DU/acre

IMPERVIOUSNESS: 31%
EFFECTIVE IMPERVIOUSNESS: 20%
WATERSHED SERVICED BY BMP: 100%
SLOPE: 4.7%
SOILS: Silt Loam soils in Glenelg Manor Series

DESIGN FEATURES

STORAGE VOLUME: 86,000 cubic feet
56% of storage for control of two year design storm. 44% of storage was for nonpoint source control.

OTHER CHARACTERISTICS:
- high length to width ratio
- well vegetated pond bed
- water passedthrough pond within a paved channel
- energy dissapating device at outlet

MONITORING ARRANGEMENT

CHARACTERISTICS: Type "H" flumes installed at inlet and outlet of pond. Manning automated samplers took flow integrated water quality samples.

STORM EVENTS MONITORED: 25 synoptic storms were monitored between October 1980 and December 1981, 47 at the inflow, 33 at the outflow.

METHOD(s) USED TO CALCULATE EFFICIENCY

Variation of Method C (Section 2, Long Term Removal Efficiency). Influent and effluent loads were calculated for thirty synoptic storms, using measured EMC's and influent discharge. (For explanation see section in this chapter headed Methods Used Analyzing BMP Removal Efficiencies).

OTHER NOTES

For reasons which are not entirely clear, Stedwick did not achieve designed detention times. Average detention was approximately 4 to 8 hours throughout monitoring period.

TABLE 6
BMP FACT SHEET

GENERAL FEATURES

FACILITY NAME: BURKE POND
TYPE OF BMP: Stormwater Retention Pond (WET POND)
LOCATION: Suburban Fairfax County, Virginia

OPERATION: In addition to the required "dry" stormwater management volume, the basin has a permanent pool of water. Water level is determined by the height of the riser and the release of the outflow pipe.

POLLUTANT REMOVAL MECHANISM(s)

Several removal mechanisms are believed to operate in wet ponds. Settling and chemical flocculation should be pronounced due to presence of standing water, and biological uptake by plankton and rooted aquatic vegetation are another candidate for removal as well.

WATERSHED CHARACTERISTICS

DRAINAGE AREA: 27.1 acres
LAND USE: Medium Density Residential
DENSITY: 3 DU/acres

IMPERVIOUSNESS: 34%
EFFECTIVE IMPERVIOUSNESS: 25%
WATERSHED SERVICED BY BMP: 100%
SLOPE: 4.5%
SOILS: Silt loams in Glenag/ Glenville series

DESIGN FEATURES

STORAGE VOLUME: 353,000 cubic feet
Permanent pool represented 34% of total storage capacity

OTHER CHARACTERISTICS:
- Average surface area = 0.9 acres
- Maximum surface area = 1.4 acres
- Mean Depth ranged from 3.3 to 3.5 feet
- Significant emergent rooted aquatic vegetation around perphery of pond

MONITORING ARRANGEMENT

CHARACTERISTICS: Palmer-Bowlus Flumes installed at inlet and outlet of pond. Mannings automated sampler, ISCO flow meter.

STORM EVENTS MONITORED: 29 synoptic storms were monitored between November 1980 to October 1981, 60 inflow storms, 33 outflow storms.

METHOD(s) USED TO CALCULATE EFFICIENCY

Method A, B and C were used. (For explanation see section in this chapter headed Methods Used Analyzing BMP Removal Efficiencies).

OTHER NOTES

Outflows over the monitoring period were only 63% of inflow volume over the 12 month monitoring period. This reflects the fact that 27 storms which were recorded at the inlet were not registered at the outlet. Most of these storms were very small (less than .15 cfs) and suggest that significant drawdowns occurred within the pond for these small storms.

Therefore, the results of the efficiency analysis for this pond are probably quite conservative, since methods A and B were predicated on relative water balance between the inlet and outlet.

TABLE 7
BMP FACT SHEET

GENERAL FEATURES

FACILITY NAME: WESTLIEGH
TYPE OF BMP: Stormwater Retention Pond (WET POND)
LOCATION: In the Westliegh subdivision, in western Rockville, Maryland

OPERATION: In addition to the required "dry" stormwater management, the basin has a permanent pool of water. Water level within the pond is regulated by the height of the riser, and also governed by the diameter of the outflow pipe.

POLLUTANT REMOVAL MECHANISM(s)

Several removal mechanisms are believed to operate in wet ponds. Physical settling and chemical flocculation are thought to be enhanced because of the interaction between the standing water and incoming runoff. Biological uptake by plankton and rooted aquatic vegetation is also believed to be important.

WATERSHED CHARACTERISTICS

DRAINAGE AREA: 48 acres
LAND USE: Large Lot Single Family Household
DENSITY: 1.2 DU/acres

IMPERVIOUSNESS: 24%
EFFECTIVE IMPERVIOUSNESS: 16%
WATERSHED SERVICED BY BMP: 100%
SLOPE: 7.9%
SOILS: Silt loams in Gleneg/ Manor/Elioak Series

DESIGN FEATURES

STORAGE VOLUME: 389,000 cubic feet
Permanent pool was 57% of total storage capacity

OTHER CHARACTERISTICS:
- Wet Pond Surface Area = 1.2 acre
- Maximum Surface area = 1.5 acre
- Mean Depth ranged from 4.1 to 6.2 acre

MONITORING ARRANGEMENT

CHARACTERISTICS: 42" Palmer-Bowlus Flume installed at inlet to pond, 2.5 foot Type "H" Flume installed at outlet - Manning sampler, ISCO flow meter.

STORM EVENTS MONITORED: 45 storm events were monitored between October 1980 and December 1981, 29 storms were synoptic.

METHOD(s) USED TO CALCULATE EFFICIENCY

Methods A, B and C. (For explanation see section in this chapter headed Methods Used Analyzing BMP Removal Efficiencies).

OTHER NOTES

TABLE 8
BMP FACT SHEET

GENERAL FEATURES

FACILITY NAME: FAIR OAKS
TYPE OF BMP: Stormwater Retention Basin (WET POND)
LOCATION:

OPERATION:

POLLUTANT REMOVAL MECHANISM(s)

WATERSHED CHARACTERISTICS

DRAINAGE AREA: 55 acres
LAND USE: Suburban Shopping Center
DENSITY: N/A

IMPERVIOUSNESS: 90%
EFFECTIVE IMPERVIOUSNESS: 90%
WATERSHED SERVICED BY BMP: 100%
SLOPE: Not determined
SOILS: Fill Soils

DESIGN FEATURES

STORAGE VOLUME: 32,250 cubic feet

OTHER CHARACTERISTICS:

MONITORING ARRANGEMENT

CHARACTERISTICS: 60" Palmer-Bowlus Flume installed at inlet, 2.5' Type "H" Flume installed at outlet. Hannings automated sampler with ISCO flow meter.

STORM EVENTS MONITORED: no synoptic storms were measured. Inlet station operated from September 1981 to January 1982, and 11 storms were monitored.

METHOD(s) USED TO CALCULATE EFFICIENCY

No estimates were calculated at this site. (For explanation see section in this chapter headed Methods Used Analyzing BMP Removal Efficiencies).

OTHER NOTES

Outlet riser was discovered to leak substantially. Because of this no pollutant removal efficiency estimates could be made. Inlet data, however, was used to establish efficiencies for the Rockville porous pavement site, along with 208 data for similar shopping centers sites.

TABLE 9
BMP FACT SHEET

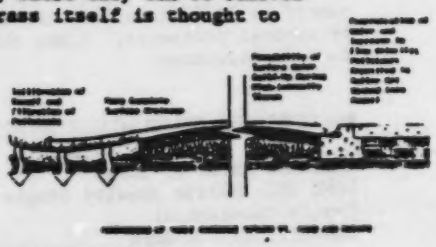
GENERAL FEATURES

FACILITY NAME: DUFIEF
TYPE OF BMP: Roadside Grassed Swale
LOCATION: Near Gaithersburg, Maryland in the Dufief Subdivision

OPERATION: Stormwater runoff from residential areas is conveyed along a vegetated depression (see figure below) instead of conventional curb and gutter conveyance systems. Runoff follows these grassed water-ways, which are connected by driveway outlets. At the terminus of the swales, a storm sewer collects runoff.

POLLUTANT REMOVAL MECHANISM(s)

Grassed swales are believed to filter out pollutants by allowing runoff to infiltrate into the soil profile, where they can be removed by various natural processes. Also, the grass itself is thought to filter out some particulates.



WATERSHED CHARACTERISTICS

DRAINAGE AREA: 12 acres
LAND USE: Large Lot Single Family Residential
DENSITY: 2.2 DU/acres

IMPERVIOUSNESS: 19%
EFFECTIVE IMPERVIOUSNESS: 11%
WATERSHED SERVICED BY BMP: 100%
SLOPE: 8.5%
SOILS: Silt loams in the Glenelg series, HG "B"

OTHER CHARACTERISTICS:
- Mean Swale length - 423 feet
- Mean Swale slope - 5.1%

MONITORING ARRANGEMENT

CHARACTERISTICS: A Type "H" Flume was installed at the downstream terminus of the swale. This flume was integrated with a Manning automated sampler.

STORM EVENTS MONITORED: 8 events were monitored from February 1981 through November 1981.

METHOD(s) USED TO CALCULATE EFFICIENCY

Methods B and D were applied using the Westleigh Pond inflow monitor as the control site. (For explanation see section in this chapter headed Methods Used Analyzing BMP Removal Efficiencies).

OTHER NOTES

The extremely small size of the sampling effort probably does not represent an adequate basis to draw any conclusions about efficiency. In most efficiency calculations, the Dufief data set was pooled with the Stratton Woods data-set to get a statistically significant sample.

TABLE 10
BMP FACT SHEET

GENERAL FEATURES

FACILITY NAME: FAIRRIDGE
TYPE OF BMP: Roadside Grassed Swale
LOCATION: Montgomery Village, Montgomery County, Maryland

OPERATION: Stormwater runoff from residential areas is conveyed along a vegetated (grassed) depression along the road, instead of by the conventional curb and gutter systems. Runoff passes under driveways within underground galvanized culvert. A stormwater sewer collects the runoff at the terminus of the swale.

POLLUTANT REMOVAL MECHANISM(s)

Grassed swales are believed to filter out pollutants by allowing runoff to infiltrate into the soil profile, where they can be removed by natural processes. Also, the grass is expected to filter out some particulates.

WATERSHED CHARACTERISTICS

DRAINAGE AREA: 19 acres
LAND USE: Medium Density Single Family Residential
DENSITY: 2.8 DU/acre

IMPERVIOUSNESS: 34%
EFFECTIVE IMPERVIOUSNESS: 21%
WATERSHED SERVICED BY BMP: 90%
SLOPE: 4.3%
SOILS: Silt loams in Glenelg/ Manor series

DESIGN FEATURES

STORAGE VOLUME: N/A

OTHER CHARACTERISTICS:
- Mean swale length - 445 feet
- Mean swale slope - 4.1%

MONITORING ARRANGEMENT

CHARACTERISTICS: 30" Palmer-Bowlus Flume installed at the terminus of the swale, equipped with a Manning automated sampler and an ISCO flow meter

STORM EVENTS MONITORED: 50 storm events were monitored between October 1980 to December 1981

METHOD(s) USED TO CALCULATE EFFICIENCY

Methods B and D were applied using Fairridge as the experimental site, and the Burke Pond inlet data as the control. (For explanation see section in this chapter headed Methods Used Analyzing BMP Removal Efficiencies).

OTHER NOTES

TABLE 11
BMP FACT SHEET

GENERAL FEATURES

FACILITY NAME: STRATTON WOODS
TYPE OF BMP: Grassed Roadside Swale
LOCATION: Stratton Woods subdivision in Reston, Virginia

OPERATION: Stormwater runoff from residential areas is conveyed along a vegetated depression along the road, instead of by conventional curb and gutter systems. Runoff follows from grassed swale to grassed swale until it is finally collected by a storm sewer. Galvanized culverts under driveways connect the swales.

POLLUTANT REMOVAL MECHANISM(s)

Grassed swales are believed to filter out pollutants by allowing runoff to infiltrate into the soil profile, where they can be removed by natural processes. Also, the grass itself is expected to filter out some particulates.

WATERSHED CHARACTERISTICS

DRAINAGE AREA: 9.5 acres
LAND USE: Large Lot Single Family Residential
DENSITY: 1.8 DU/acres

IMPERVIOUSNESS: 22%
EFFECTIVE IMPERVIOUSNESS: 17%
WATERSHED SERVICED BY BMP: 100%
SLOPE: 1.6%
SOILS: Sandy, Silt and Silt Loams in the Brockrock/Penn/Croton series

DESIGN FEATURES

STORAGE VOLUME: N/A

OTHER CHARACTERISTICS:
. Mean Swale length - 260 feet
. Mean Swale slope - 1.8%

MONITORING ARRANGEMENT

CHARACTERISTICS: 27" Palmer-Bowlus Flume at outlet.

STORM EVENTS MONITORED: 33 storm events were monitored between October 1980 and October 1981.

METHOD(s) USED TO CALCULATE EFFICIENCY

Methods A and D using the Westliegh inflow data as the control. (For explanation see section in this chapter headed Methods Used Analyzing BMP Removal Efficiencies).

OTHER NOTES

TABLE 12
BMP FACT SHEET

GENERAL FEATURES

FACILITY NAME: BURKE VILLAGE SHOPPING CENTER
TYPE OF BMP: Infiltration Trench
LOCATION: Burke, Virginia

OPERATION: A trench was installed adjacent to shopping center parking lot which consisted of a small excavated pit backfilled with coarse stone. This trench was connected to the storm drain system with a small outlet pipe.

POLLUTANT REMOVAL MECHANISM(s)

The trench is intended to provide temporary storage of stormwater followed by gradual infiltration into the underlying soil profile, and eventual release through the pipe. Pollutant removal is assumed to occur within the soil profile, or by diversion to groundwater.

WATERSHED CHARACTERISTICS

DRAINAGE AREA: 4.5 acres
LAND USE: Shopping Center
DENSITY: N/A

IMPERVIOUSNESS: 79%
EFFECTIVE IMPERVIOUSNESS: 79%
WATERSHED SERVICED BY BMP: 59%
SLOPE: Not determined
SOILS: Silt Loams in the Glenelg/Worsham Series HG "B"

DESIGN FEATURES

STORAGE VOLUME: 11,240 cubic feet of void space

OTHER CHARACTERISTICS:
- the void space represents approximately 1/2 to 1/3 of the volume required to control the two year design storm

MONITORING ARRANGEMENT

CHARACTERISTICS: 27 inch Palmer-Bowlus Flume at outlet.

STORM EVENTS MONITORED: 51 events monitored between September 1980 through December 1981.

METHOD(s) USED TO CALCULATE EFFICIENCY

Methods A and D using the Fair Oaks inflow data as a control. (For explanation see section in this chapter headed Methods Used Analyzing BMP Removal Efficiencies).

OTHER NOTES

TABLE 13
BMP FACT SHEET

GENERAL FEATURES

FACILITY NAME: DANDRIDGE
TYPE OF BMP: Infiltration Pit
LOCATION: Townhouse development at the Fairfax/Vienna line, in Virginia

OPERATION: Stormwater from the townhouse development was directed into three parallel subsoil gravel trenches, which were drained by 6" perforated tile drains and conveyed to an outlet.

POLLUTANT REMOVAL MECHANISM(s)

Rapid infiltration into the soil profile was hypothesized to filter out particulate pollutants. Also, some component of the total runoff load was expected to be routed to the groundwater.

WATERSHED CHARACTERISTICS

DRAINAGE AREA: 2.5 acres
LAND USE: Townhouse
DENSITY: 16 DU/acre

IMPERVIOUSNESS: 55%
EFFECTIVE IMPERVIOUSNESS: 34%
WATERSHED SERVICED BY BMP: 48%
SLOPE: 3.6%
SOILS: Silt Loams in Glenelg Series, HG "B"

DESIGN FEATURES

STORAGE VOLUME: 4,060 cubic feet of void space

OTHER CHARACTERISTICS:
. perforated 6" tile drains

MONITORING ARRANGEMENT

CHARACTERISTICS: 1.5" Palmer-Bowlus Flume installed at outlet of tile drains

STORM EVENTS MONITORED: 46 storm events monitored between September 1980 through December 1981.

METHOD(s) USED TO CALCULATE EFFICIENCY

Methods B and D using Lakeridge and Stedwick inflows as a control. (For explanation see section in this chapter headed Methods Used Analyzing BMP Removal Efficiencies).

OTHER NOTES

At the Dandridge site, slightly over 50% of the runoff monitored at the outflow site was from uncontrolled areas (i.e., drainage not entering the infiltration device. This feature may be responsible for masking some of the potential pollutant removal which might have taken place.

TABLE 14
BMP FACT SHEET

GENERAL FEATURES

FACILITY NAME: ROCKVILLE CITY CENTER
TYPE OF BMP: Porous Pavement Site
LOCATION: Rockville, Maryland

OPERATION: Stormwater collected from 2.2 acres of conventional pavement passed over porous pavement section (2.0 acres). The porous pavement was of the "popcorn" pore variety. Stormwater passed below pavement through a gravel bed into the soil drain, and was collected by 6" perforated tile drains. This water is subsequently conveyed to the outlet monitoring area.

POLLUTANT REMOVAL MECHANISM(s)

Rapid infiltration of stormwater through pores in the asphalt, and subsequent adsorption to binding sites within the soil matrix were hypothesized to remove a significant percentage of pollutants by chemical, physical and biological processes. Also some component of the runoff volume is assumed to be lost to the groundwater.

WATERSHED CHARACTERISTICS

DRAINAGE AREA: 4.2 acres
LAND USE: Office Complex
DENSITY: N/A

IMPERVIOUSNESS: 70%
EFFECTIVE IMPERVIOUSNESS: 70%
WATERSHED SERVICED BY BMP: 48%
SLOPE: 2.6%
SOILS: Silt Loams in the Glenelg Series, HG "B"

DESIGN FEATURES

STORAGE VOLUME: 27,400 cubic feet of void space in the 2 acre porous pavement area.

OTHER CHARACTERISTICS:

MONITORING ARRANGEMENT

CHARACTERISTICS: 0.75' Type "H" Flume installed at stormwater conveyance system below the tile drains.

STORM EVENTS MONITORED: 35 storm events between February and November, 1980.

METHOD(s) USED TO CALCULATE EFFICIENCY

Method "B", comparing the median loading rates from the Fair Oaks site and at two 208 shopping center sites. (For explanation see section in this chapter headed Methods Used Analyzing BMP Removal Efficiencies).

OTHER NOTES

METHODS FOR MONITORING BMPs

The field sampling for the monitoring of urban BMP pollutant removal effectiveness was conducted by Virginia Polytechnic Institute's Occoquan Watershed Monitoring Laboratory (OWML). This section briefly summarizes this field sampling program conducted between September 1980 and January 1983. A complete description of the equipment installations and procedures used in field sampling can be found in Chapters 2 through 6 in the Final VPI Contract Report (OWML, 1983). The reader is encouraged to examine the VPI report closely to learn more about the site instrumentation, field and lab methods, and data management techniques which were an integral part of the overall project.

Major Features of the Monitoring Apparatus

Most of the BMP sites generally involved discharges from pipes or regularly configured man-made channels. Therefore, primary flow measuring devices could be easily installed at most sites. Palmer-Bowlus flumes were used at sites with round pipes, whereas Type-"H" flumes were generally utilized at sites with well defined channels. Discharge rating tables were established for all primary flow measurement devices, and a bubbler type flow-meter and EPROM chip were used to convert stage measurements to flow readings in the field. This allowed automated composite sampling of desired water quality parameters.

Runoff samples were collected using Manning S-4040 portable automated samplers. The Manning sampling devices use vacuum techniques to withdraw samples, and possess a special metering chamber to ensure that equal volumes are collected during each sample activation.

All data on station flows and periods of sample activation were recorded and stored on cassette tape using a portable control data logger, for eventual reduction on the VPI computer. Maintenance of accurate flow and sampler activated records was critical to the assurance of representative sample compositing at the field monitoring sites. End products of the sampling methods employed were flow weighted composite samples which could be easily reduced into an event mean concentration (EMC) value for individual storms. The configuration of equipment at a typical monitoring station is shown in Figure 1.

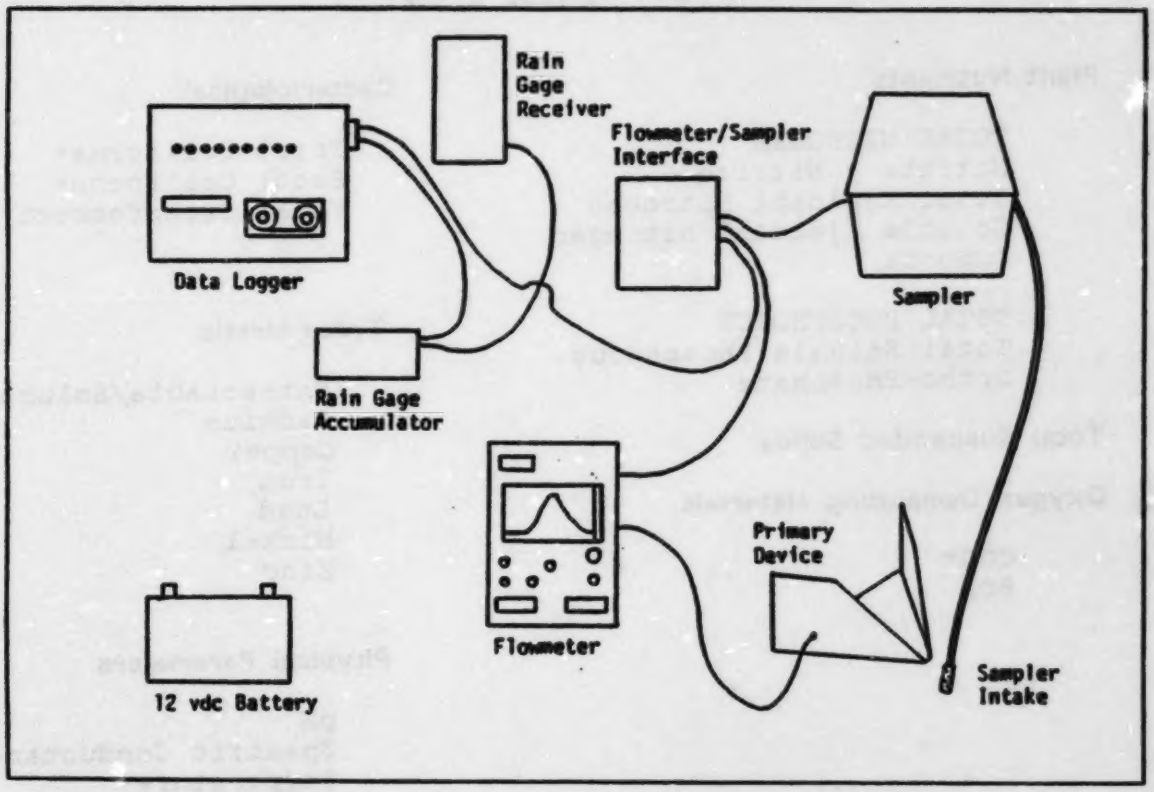
Monitoring equipment was housed in mounted fiberglass enclosures. Each station was visited by OWML personnel at least once a week to perform routine maintenance and verification checks. Stormwater runoff samples were collected within 12 hours of the activation of the field sampler, refrigerated, and transported to the laboratory. Samples were analyzed using accepted analytical techniques (which are summarized in Table 5.2 of the OWML contract report, (OWML, 1983) along with the quality assurance/quality control plan). Measurements were made for plant nutrients, suspended solids, organics, heavy metals, bacteriological forms, and various physical parameters. A complete list of the parameters analyzed can be found in Table 15.

Monitoring Arrangements for Different BMP Types

The monitoring arrangement for each of the BMPs varied considerably. For the dry and wet pond BMPs, stations were installed at the inlet and outlet of each structure. This allowed for a direct comparison of Event Mean Concentrations (EMCs) in runoff entering and leaving the BMP (after correcting for the potential for slightly different drainage areas at the inlet and outlet of the pond).

Figure 1

Monitoring Setup For Urban BMP Sampling



SOURCE: Occoquan Watershed Monitoring Laboratory, 1983.

TABLE 15

PARAMETERS ANALYZED IN THE BMP-EFFECTIVENESS STUDY

Plant Nutrients

TOTAL NITROGEN
Nitrate + Nitrite
Total Kjeldahl Nitrogen
Soluble Kjeldahl Nitrogen
Ammonia

TOTAL PHOSPHORUS
Total Soluble Phosphorus
Ortho-Phosphate

Total Suspended Solids

Oxygen Demanding Materials

COD*
BOD

Bacteriological

Total Coliforms*
Fecal Coliforms*
Fecal Streptococci*

Trace Metals

Extractable/Soluble
Cadmium
Copper
Iron
Lead
Nickel
Zinc

Physical Parameters

pH
Specific Conductance
Temperature*

* Periodic.

Because infiltration controls accept diffuse runoff flows from a broad area it is not physically possible to monitor inflow runoff quality at volume-control BMPs sites (i.e., grassed swales, infiltration devices, porous pavements). Therefore monitoring only occurred at the point where runoff was discharged from infiltration structures. The study design called for sampling equipment to be installed at the outlet of each structure, and for comparisons of observed loading data from the outlet to be made with loading data from similar land use types which were monitored without any BMP controls. Loading comparisons were made between sites having similar land use, density, and degree of imperviousness. It was not possible to pair controlled and uncontrolled sites of similar land use which also had the same general location and precisely the same soil and slope characteristics. Because of this experimental limitation, the results of the BMP efficiency analysis for volume control devices should be viewed as providing general comparisons of relative pollutant removal behavior rather than precise removal rates.

METHODS USED FOR ANALYZING BMP POLLUTANT REMOVAL EFFICIENCIES

A variety of methods were employed to develop removal efficiency estimates for each of the urban BMP's analyzed. The methods used in each case were dependent on the monitoring arrangement for the BMP site as well as the suitability of the data set for analysis (e.g. the number of synoptic storms monitored). Removal estimates were based on both arithmetic and statistical methods. These general methods are described in detail below:

Method A: Mean Storm Event Efficiency

This method was applied only to wet and dry pond BMPs which had an operating sampling monitor at both the inlet and outlet of the structure. As such, it could not be applied to evaluate volume control BMP efficiencies.

Synoptic storms (i.e., events monitored at both inlet and outlet) were screened to identify those pairs in which inflow and outflow were in reasonable agreement. These resulting pairs were then normalized to account for water balance errors such as pond drawdown due to evaporation loss in wet ponds. Other adjustments included corrections to account for difference in the drainage areas of inflow and outflow monitoring points by converting observed EMC's into loading rates (i.e., lbs/acre). Pollutant removal efficiency was calculated for each event using the formula shown in Figure 2. Individual storm event efficiency estimates were subsequently summed and divided by the number of storms to arrive at the mean or average removal rate.

Figure 2

Mean Removal Rate

Removal Efficiency Calculated for each Synoptic Storm:

$$RR_s = 1 - \frac{\text{Outflow Load}}{\text{Inflow Load}} \times 100$$

and summed:

$$\frac{\sum_{s_1}^{s_n} RR_s}{N_s}$$

For example:

If $RR_{s_1} = -10$
$RR_{s_2} = -8$
$RR_{s_3} = +25$
$RR_{s_4} = -7$

Then the mean removal rate is 0%

Method B: Median Loading Rate Reduction

An alternative approach for calculating removal efficiencies was employed which utilized the entire data-set which was generated at each BMP station. In this method, the event mean concentration (EMC) for each storm was multiplied by the total flow, and normalized to account for area and depth of runoff. The resulting storm load was expressed in pounds per acre per inch of runoff. The entire population of inflow and outflow storm loads for all events were analyzed statistically, and the storm loadings at the inlet and outlet for the median loading event were directly compared. Figure 3 illustrates how removal rates were computed by this method.

Method C: Long Term Removal Efficiency

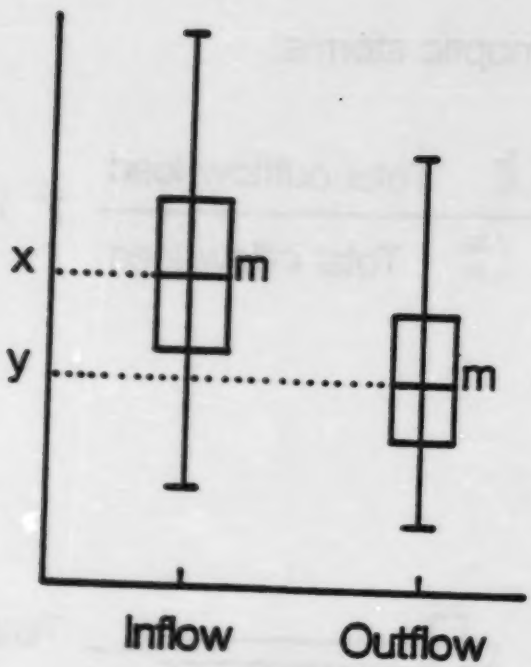
The previous two methods were oriented toward providing removal estimates for a particular kind of storm event or loading condition. Of perhaps greater interest to engineers and planners is the typical long term removal efficiency for a given BMP, since the variation in efficiency for individual storm events can often be significant. This long term estimate is conceptually simple in nature. Basically, mass loadings measured entering and leaving the pond over the entire monitoring interval were summed separately and evaluated using the formula shown in Figure 4.

Method D: Stepwise Linear Regression Techniques

Individual efficiency estimates for individual storms were analyzed in a multivariate regression model to identify those characteristics which best

Figure 3

Median loading rate reduction



Looking at entire data population,

compare median loading rates (m)

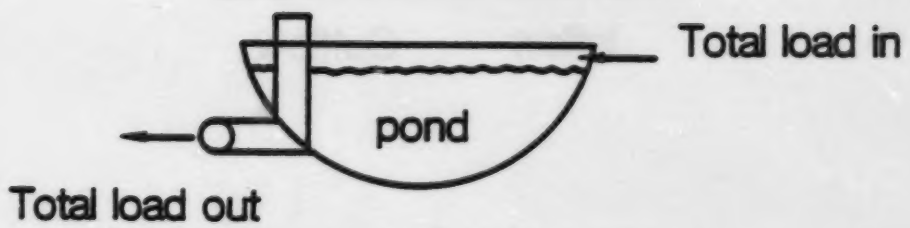
$$= \boxed{1 - \frac{y}{x} \times 100}$$

Figure 4

Long term removal efficiency

For all synoptic storms:

$$1 - \frac{\left\{\sum_{s_1}^{s_n}\right. \text{ Total outflow load}}{\left\{\sum_{s_1}^{s_n}\right. \text{ Total inflow load}} \times 100$$



describe the efficiency of wet ponds. Factors examined included drainage area, permanent pool volume, imperviousness, inflow concentration, inflow volume, and outflow volume. Of all these factors, only the latter three were found to produce a correlation that was significant at the 95 percent confidence interval. The general form of the statistical model was:

$$\text{Removal (\%)} = 100 - a(Qin)^{b_1} * (Qout)^{b_2} * (Cin)^{b_3}$$

Where

Qin = inflow runoff (inches)

Qout = outflow runoff (inches)

Cin = event mean concentration of inflow (mg/l)

a, b_1, b_2, b_3 = regression coefficients

A complete discussion of this model, along with an evaluation of its prediction accuracy can be found in pages 74-76 of the NVPDC final NURP contract report (NVPDC, 1983). Essentially, this technique was used to provide an indication as to the behavior of individual pollutants within wet ponds under varying storm conditions. As such, it serves to increase understanding about the complicated dynamics of wet ponds, and provides statistical predictions of the specific pollutant removal efficiency associated with individual storms.

Method E: Comparison of Parametric Statistics

For volume controls such as grassed swales it was necessary to use traditional parametric statistics to test for differences in runoff and unit area pollutant loads between runoff outflows from the BMP structure and from uncontrolled sites having similar land uses. All tests assumed

a log-normal data distribution, and were only applied to equivalent runoff distribution data. Three different parametric statistical tests were used to identify differences in loading distributions at the 95% confidence interval. These included:

One-sided K-S testing procedures to test for differences in loading distributions of the controlled and uncontrolled runoff datasets.

T-statistics testing procedures to determine whether the mean loading rates of the BMP dataset is different from its control.

F-Statistics testing procedures to check for significant differences in variances between experimental and control sites.

Method F: Comparisons of Non-parametric Statistics

Another set of statistical tests was performed as an additional check on the statistics generated by METHOD E. These tests emphasized the distribution free description of the data and involve the ranking of the data values.

Two sided K-S procedures designed to test for significant differences in the data distribution in experimental and control sites.

Wilcoxian Rank-Sum procedures which test for difference in central values (i.e., the median) of the experimental and control data sets.

RESULTS OF THE BMP-EFFECTIVENESS ANALYSIS

In this section, an analysis of the pollutant removal effectiveness of the individual BMP types which were monitored is presented. Reference is also made to the comparative efficiency of different BMPs.

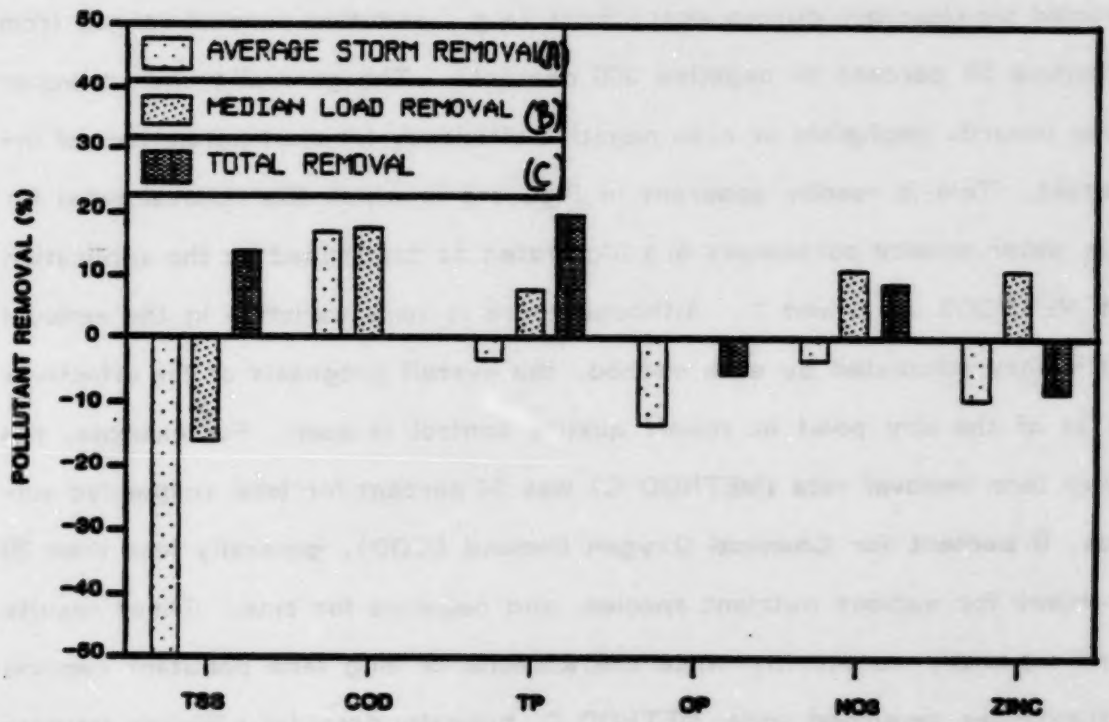
Dry Stormwater Ponds

Overall, the dry pond investigated in the Washington area NURP study did not perform as an effective best management practice. Removal rates varied considerably during most storms (e.g., sediment removal ranged from positive 98 percent to negative 300 percent). The general trend, however was towards negligible or even negative efficiency for most parameters of interest. This is readily apparent in Figure 5 in which the removal rates for six water quality parameters are illustrated as determined by the application of METHODS A, B and C. Although there is some variation in the removal efficiency calculated by each method, the overall prognosis of the effectiveness of the dry pond in runoff quality control is poor. For example, the long term removal rate (METHOD C) was 14 percent for total suspended solids, 0 percent for Chemical Oxygen Demand (COD), generally less than 20 percent for various nutrient species, and negative for zinc. These results are especially noteworthy since the estimate of long term pollutant removal effeciencies developed under METHOD C, typically provides a higher estimate of removal efficiency than either Method A or Method B.

The poor to mediocre performance observed at the dry pond site is probably related to several factors. First, the brief residence time of stormwaters within the structure (usually less than 2 hours) severely limits the degree to which physical and chemical pollutant removal can take place.

Figure 5

Comparison of Independent Methods Used to Calculate Removal Efficiencies of Dry Pond BMP'S



Secondly, the lack of permanent water storage precludes removal by biological means. Thirdly, the substantial number of storms with negative efficiencies suggests that the poorly vegetated pond bed was prone to scour and erosion. Resuspension of previously deposited materials was also thought to be an important factor relating to poor performance of the pond.

Extended Detention Dry Ponds

Extending the duration of detention times in dry stormwater basins through modification of the outflow structure appeared to be promising as a method for improving removal efficiencies. Removal of particulate forms of urban pollutants (as calculated with METHOD C) was typically high, and on the same order of those reported for wet ponds. For example, sediment removal was approximately 64 percent, organic nitrogen removal was 30 percent, and reductions in COD were 30 percent. Removal rates for trace metals were even higher. Fifty-seven percent of the zinc and 84 percent of the lead entering the pond was retained. However, removal of soluble nutrient forms was minimal, with only 1 percent of the ortho-phosphorus and only 10 percent of the nitrate-nitrogen being removed in the long term. Removal of total nitrogen and total phosphorus was also quite low; in both cases less than 15 percent of the incoming nutrients were removed.

Much of the explanation for the improved pollutant removal performance can be directly attributed to the extended detention achieved. Although the pond did not achieve the detention times for which it was originally designed, the degree of detention which was accomplished was still sufficient to remove particulates effectively. Settling column studies conducted by VPI's OWML (1983) described later in this chapter confirm this belief. Other design features that contributed to the high removal of particulates were the paved channel at the pond's bottom and the established vegetation within the

pond bed. These features reduced the likelihood of scour or resuspension, which would tend to reduce the pollutant removal efficiency of the pond.

Wet Ponds

Wet ponds were found to be one of the most effective BMPs studied for nonpoint source control. These ponds were observed to remove a significant portion of soluble nutrient forms. As can be seen in Figure 6, the high removal rate of soluble nutrients such as ortho-phosphate and nitrate was in sharp contrast to the minimal removals noted at the dry pond and/or extended detention pond sites. These data suggest the importance of biological uptake in wet ponds as an effective removal mechanism for biologically-available nutrients. Long term removal rates for particulate pollutants in wet ponds were also high and suprisingly comparable to the rates demonstrated for extended detention ponds as shown in Figure 7. For the pooled wet ponds, removal rates for suspended sediments were 54 percent, COD removal was approximately 30 percent and organic nitrogen reductions were 15 percent. Total phosphorus reductions were 64 percent. (It should be noted that the Westleigh wet pond consistently out-performed the Burke wet pond for nearly all particulate pollutants. As mentioned in Table 6, the suspected drawdown at Burke may have caused efficiency estimates for the pond to be too conservative.)

Observed removal rates for trace metals were also consistently high. Pooled long term removals for zinc and lead were 51 and 65 percent, respectively. The deposition of trace metals within pond sediments was confirmed in sampling conducted within the pond bed (OWML, 1983). Pond sediments had been enriched to levels approaching the metal content of domestic sludge. However, no downward migration of these metals into the soil was observed.

Application of the METHOD D multi-variate regression model shed some interesting light on wet pond behavior. This analysis suggested that removal efficiency sharply increased for most particulate pollutants as the size of the storm increased (Figure 8). This fact helped to explain several seemingly incongruous results of the wet pond efficiency analysis. For example, removal rates for some parameters fluctuated widely from storm to storm. However, upon closer scrutiny, many of the storms with lower efficiencies were found to be of relatively small size, which was consistent with the results of the multi-variate regression models. (i.e., smaller storms were predicted to have lower removal efficiencies.) Similarly, the larger storms tended to have much greater removal efficiencies.

Figure 9 compares the removal rates observed in wet ponds for particulate pollutants such as sediment, COD, total phosphorus, with the dissolved nutrients ortho-phosphate and nitrate. The long-term removal efficiency for all storms (METHOD C) for the particulate constituents was generally higher than the removal rates estimated with either the mean (METHOD A) or median (METHOD B) efficiency. Since the large storms produce the majority of the annual load of particulate pollutants, the greatest removal efficiency is shown with the long-term method. This is also evidenced by examing those constituents which do not exhibit such a dramatic increase in load as storm size increases (such as ortho-phosphate or nitrate). For these nutrient forms, it would be expected that the three estimation methods would converge and give essentially similar results. As can be seen in Figure 9, this is exactly the behavior which was observed in wet ponds.

Operative mechanisms for achieving pollutant removal in wet ponds are manifold, including deposition, chemical flocculation/transformation and biological activity. Based on a comparison of component nitrogen efficiencies, it appears that biological uptake is the predominant removal mechanism for

Figure 6

Pollutant Removal Efficiencies Associated with Selected Pond BMP' S:Nutrients

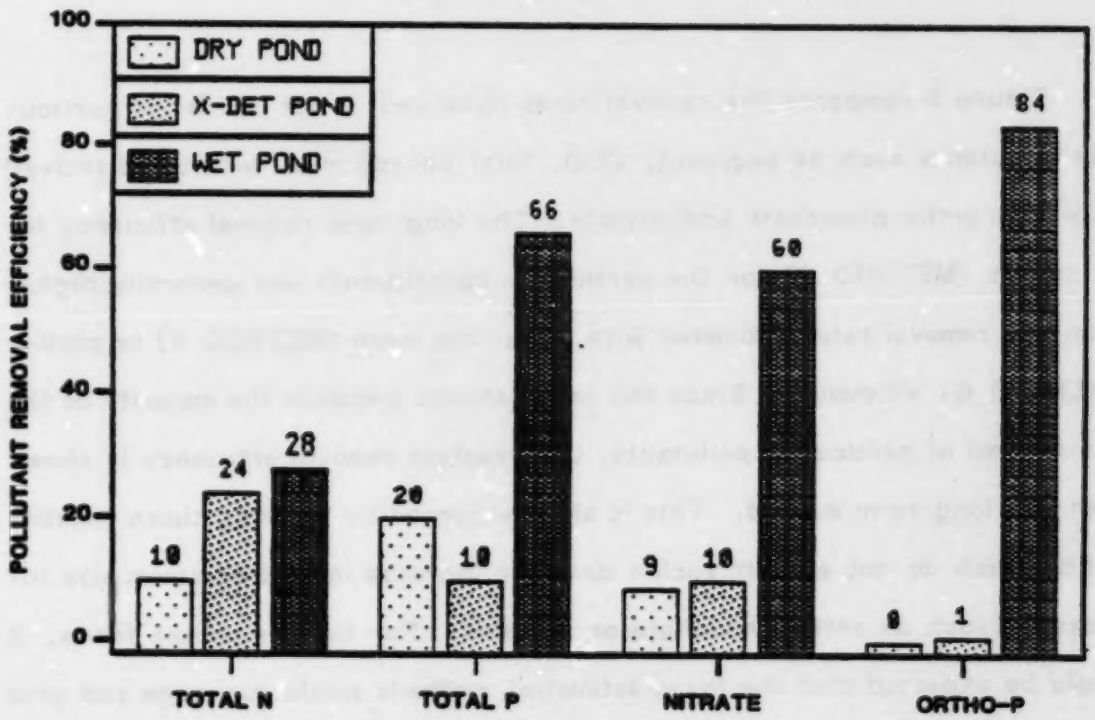


Figure 7

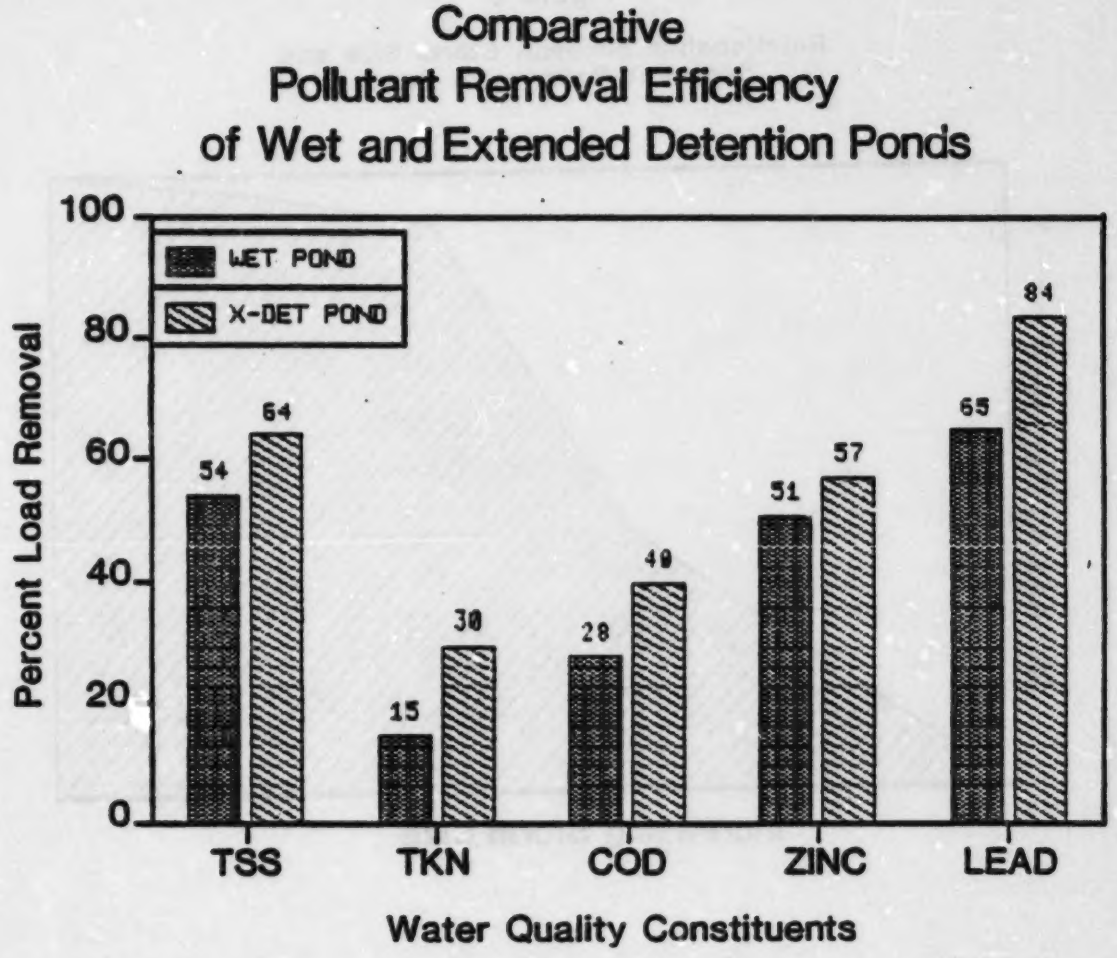

Comparative
Pollutant Removal Efficiency
of Wet and Extended Detention Ponds
WET POND
X-DET POND
Percent Load Removal
100
80
60
40
20
0
54
64
15
30
28
40
51
57
65
84
TSS
TKN
COD
ZINC
LEAD
Water Quality Constituents

Figure 8

Relationship Between Storm Size and
Sediment Removal in Ponds

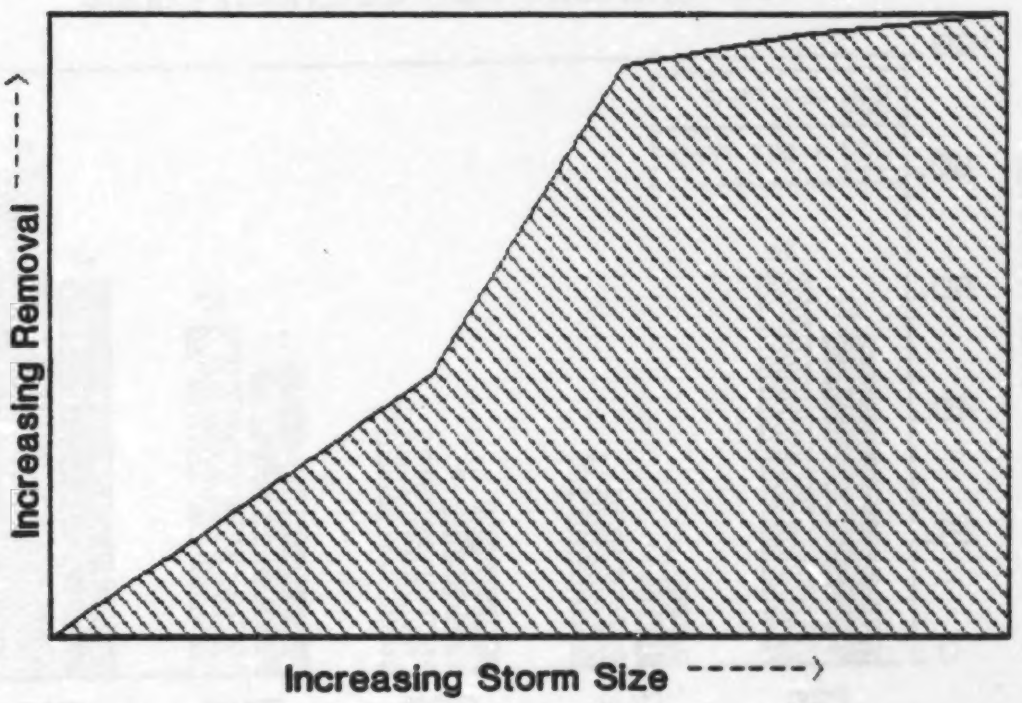
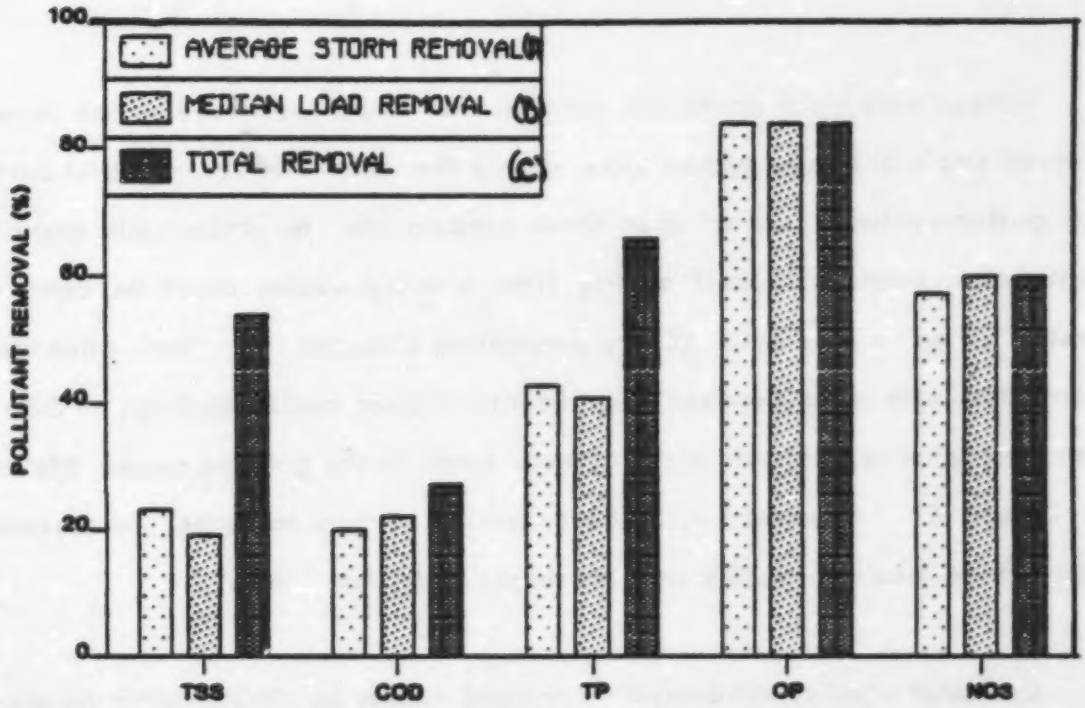


Figure 9

Comparison of Independent Methods Used to Calculate Removal Efficiencies of Wet Pond BMP'S



nitrate. Deposition, rather than oxidation, seems to be the primary removal mechanism for organic nitrogen. Depositional processes also appear to be fully capable of accounting for the organic phosphorus removal observed. Uptake by algae or routed aquatic plants seems to be the dominant removal mechanism for ortho-phosphorus. The striking similarity in removal rates observed in wet and extended detention ponds (Figure 7) implies that depositional processes, such as settling and flocculation, are more than sufficient to explain the observed patterns in removal rates for sediments, COD, and trace metals in wet ponds.

Grassed Swales

Comparisons were developed between the runoff loads leaving the three grassed swale drainage system sites versus the loads from conventional curb and gutter systems. Based upon these comparisons, no statistically significant improvement in runoff quality from grassed swales could be demonstrated for any of the water quality parameters analyzed. (In fact, when the entire data sets were analyzed, significantly higher median loadings of COD, ortho-phosphorus, ammonia and zinc were noted in the grassed swales (Method B and E). However, with the exception of zinc loadings, (discussed later) these results probably only represent statistical "noise".

Lysimeter studies conducted in grassed swales by OWML found no statistically significant enrichment of trace metals within the soil profiles underlying grassed swales when compared to adjacent curb or lawn soil metal concentrations. This finding suggests that trace metals did not settle out in the grassed swales and were not effectively removed from runoff. The presence of enhanced levels of zinc in the runoff of grassed swales could be attributed to mobilization of zinc anions from the galvanized culverts which carried runoff under the driveways at the monitored sites. Field studies by

the OWML (1983) have implicated "acid" rainfall within the region as being the principal cause of the release of zinc from these culverts.

To some degree, the effectiveness of grassed swales in removing pollutants could have been masked by differences in soils, slopes and rainfall distributions which occurred at the curb and gutter control sites. This certainly were some differences in these factors which could affect comparisons between the Stratton Woods swale and the Westleigh curb and gutter control site, and to a lesser extent, between the Dufief swale and the Westleigh control site. However, the most representative comparison, the one for Fair Ridge swale/Burke curb and gutter, indicated that this swale also had negligible or negative removal rates for the entire spectrum of pollutants analyzed. The conclusion reached was that if grassed swales have any pollutant removal capability, it certainly could not be distinguished from background loadings.

Why, then, did grassed swales appear to perform so poorly? Several reasons are offered. First, all swale sites monitored were underlain by silt loam soils, the predominant soil type in most of the Washington region. Such soils lack the porosity of other soils in C or D hydrological groupings. Second, the contact time of stormwater within the swale system was usually only on the order of 5 to 10 minutes, whereas the infiltration rate of the silt loam soils underlying the swale systems which were monitored was considerably greater. As a result, little infiltration of stormwater into the soil profile apparently occurred. Thirdly, the slopes within the swales themselves ranged from 4 to 6 percent. This probably led to high water velocity and substantial downstream head. In many of these sloping grassed swales, stormwater quickly matted the grass, and the flow regime distinctly resembled open channel conditions. Finally, the grass within the residential swales was frequently mowed, and as a result, did not act as an effective natural filter.

Research in New Hampshire (Oakland, 1983) reported low to moderate removals of particulates in a grassed swale with pure stands of 12 inch tall reed-canary grass, which suggests that dense vegetation is required to achieve a significant filtering effect.

Although no stormwater or pollutant removal benefits could be attributed to the swale sites monitored in the Washington area, it is believed that certain design modifications to swale systems could increase their effectiveness as BMP's. For example, permeable gravel filters, energy dissapators, or ponding mechanisms could be installed to slow runoff and enhance pollutant removal by infiltration. Also, application of grassed swales on more permeable soils, such as those in hydrological groups C and D, might also improve efficiencies. In addition, the implementation of swales on gentler slopes would be beneficial. And finally, the use of swales on the flat coastal plain topography and soils might be advantageous, since water velocity and downstream heads would not overwhelm the infiltration capacity within the swales.

Infiltration Controls

Results from the monitored infiltration BMP sites were somewhat difficult to assess for several reasons. First, the two sites, Burke Center and Dandridge, had different designs, storages and land uses. As a result, the removal efficiencies of these infiltration controls should be analyzed on a case by case basis. Secondly, a comparison of loadings from the Dandridge facility with runoff loadings monitored from the Stedwick Pond inflow point (which was intended to represent a similar land use unaffected by BMP controls) appeared to be inappropriate upon further field investigations of site characteristics. Due to apparent discrepancies between the site plans for the area drainage system with actual on-site grading and drain construction, it was

discovered, after the monitoring data had been collected and analyzed, that over half the loads monitored at Dandridge were not controlled by the infiltration system. Also, its control site had a different precipitation distribution and had 20 percent less imperviousness cover within its drainage area. While none of these factors alone would prevent the development of useful comparisons, it was felt that in combination they tended to significantly bias the results against the infiltration facility. This was seen in the median loading rate removals calculated for Dandridge infiltration facility. For sediment, total nitrogen, COD, Zinc, and Lead, negative efficiencies were recorded in excess of 66 percent (and ranging up to -267 percent). It would be difficult to conceive a mechanism having such prolific pollutant generation in the absence of any known sources of pollutants within the device itself. As a result, the Dandridge/Stedwick site comparison was judged to be invalid, and as such, the comparison was not considered to be representative of pollutant removal benefits attributed to volume controls. Unfortunately, there was no other Washington area NURP site which has similar characteristics to Dandridge which could be used for comparison.

Fortunately, the Burke Center infiltration trench/Fair Oaks control comparison was much more representative. In general, the Burke Center infiltration trench was found to have significant potential as an effective BMP. Median loading rate reductions on the order of 50 percent were observed for sediments and trace metals. COD removal was estimated to be 37 percent. Nutrient removal, however, was negligible or non-existant. (This is not altogether suprising since there are in all likelihood very few biological removal mechanisms operating within the coarse gravel of the Burke trench). These removal estimates, must be considered provisional given the inherent limitations of the comparisons noted earlier. Also, the Burke Center infiltration trench is only one of many kinds of designs for infiltration structures. As such, the removal estimate strictly applies only to the Burke

trench site. Further field research is being planned by the Maryland Department of Natural Resources to investigate the effectiveness of other infiltration design concepts.

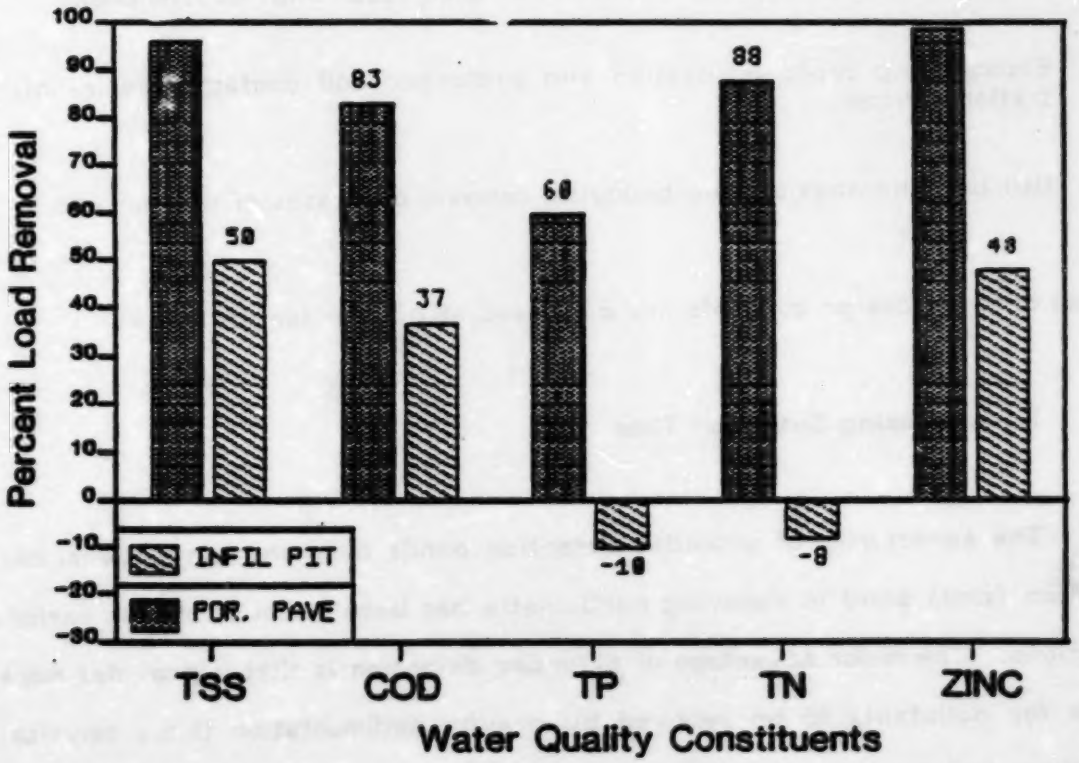
Porous Pavement

The porous pavement site proved to be a very effective best management practice with respect to control of both water quantity and quality. For most storms, the duration of the runoff event was extended by up to 24 hours, and peak discharges were dramatically shaved. Extremely high removal rates (in excess of 80 percent) were observed for sediments, COD, total nitrogen and trace metals (see Figure 10). Removal of phosphorus and soluble nitrogen forms was also in excess of 60 percent. These removal rates were calculated with Method B using the Fair Oaks inflow and two shopping centers monitored during an earlier study (NVPDC and VPI&SU, 1978) as uncontrolled equivalent sites for the sake of comparison. As can be seen in Figure 10, the removal efficiency for the porous pavement site was considerably greater than the second most efficient infiltration device, the Burke Center infiltration device.

The chief removal mechanisms that appeared to be operating to such great effect in the porous pavement site were the rapid and complete infiltration runoff into the soil profile, and subsequent adsorption, trapping and chemical decay within this zone. Also, a sizeable component of the runoff and pollutant load may have been routed to the groundwater pool, and thus be removed.

Figure 10

Comparative Pollutant Removal Performance
Porous Pavement and Infiltration Trench



DISCUSSION: GENERAL DESIGN FEATURES WHICH ENHANCE POLLUTANT REMOVAL IN STORMWATER MANAGEMENT DEVICES

The results obtained in the analysis of runoff loading data from individual BMPs and the special studies conducted by OWML suggest several design principles that can enhance the pollutant removal capability of urban stormwater management structures. These principles are:

- Extending detention times in conventional "dry" stormwater ponds.
- Preparing the bed of dry ponds to minimize scour and resuspension.
- Encouraging rapid infiltration and prolonged soil contact time in infiltration devices.
- Utilizing the physical and biological removal processes of wet ponds.

Each of these design concepts are discussed at greater length below.

1. Increasing Detention Time

The superiority of extended detention ponds over the conventional detention (dry) pond in removing particulates has been demonstrated in earlier sections. The major advantage of extended detention is that it provides more time for pollutants to be removed by gravity sedimentation (i.e., physical settling and coagulation). This impression is reinforced by settling column experiments conducted by the OWML as a special study for the NURP project.

In this experiment, seven urban stormwater samples collected from commercial areas were introduced into a six foot plexiglass settling chamber. Sampling ports were located at every foot along the settling chamber, and

samples were withdrawn at intervals of 2, 6, 12, 24 and 48 hours. The downward movement of pollutants was measured, and a removal rate was calculated, based on the percentage of influent concentration which migrated to a four foot depth.

These experiments provided data that shed some interesting light on the settling dynamics of urban stormwater, and on the degree of removal which could be achieved through settling processes alone. One important result was that the settling rate for most parameters was extremely sensitive to the initial concentrations, such that the highest settling rates were almost always associated with the stormwater samples which had the greatest initial concentration (Figure 11). Also, most of the constituents in the stormwater runoff samples behaved like a mixture of discrete and flocculant solids, with discrete solids rapidly settling out (within a few hours) while the flocculant solids gradually settled over a period of several days. The practical implication of this phenomenon is that the removal rate for most constituents was logrithmic in nature. This is best exemplified in the sediment settling data illustrated in Figure 11. As can be seen, 65 percent of the sediment removal occurs within the first six hours, while the next 15 percent removal increment takes another 42 hours to occur. Therefore, the design of extended detention ponds could be oriented toward achieving a 6 to 12 hour detention time, and still achieve significant percentage of the long-term pollutant removal rate. As can be seen in Figure 12, at least two-thirds of the potential removal occurs within the first six hours for nearly all water quality parameters.

The next phase of analysis is an attempt to provide information of what those maximum removal efficiencies could theoretically be for individual water quality parameters. To this end, the settling column data was interpreted in the light of median stormwater runoff concentrations observed in all of the

Figure 11

Relationship Between Sediment Removal Rate, Influent Concentration and Sedimentation Time Experimental Settling Column Studies

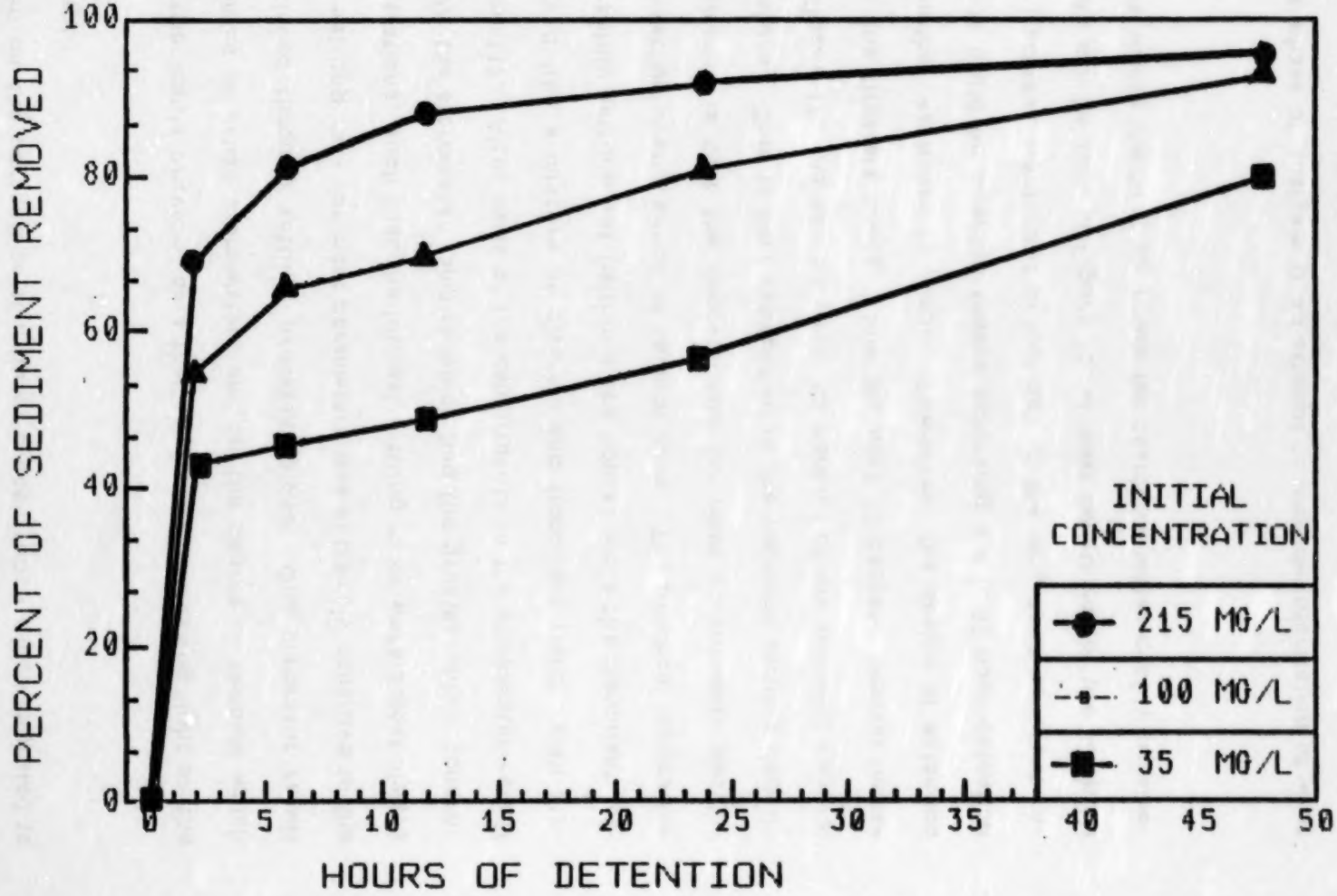
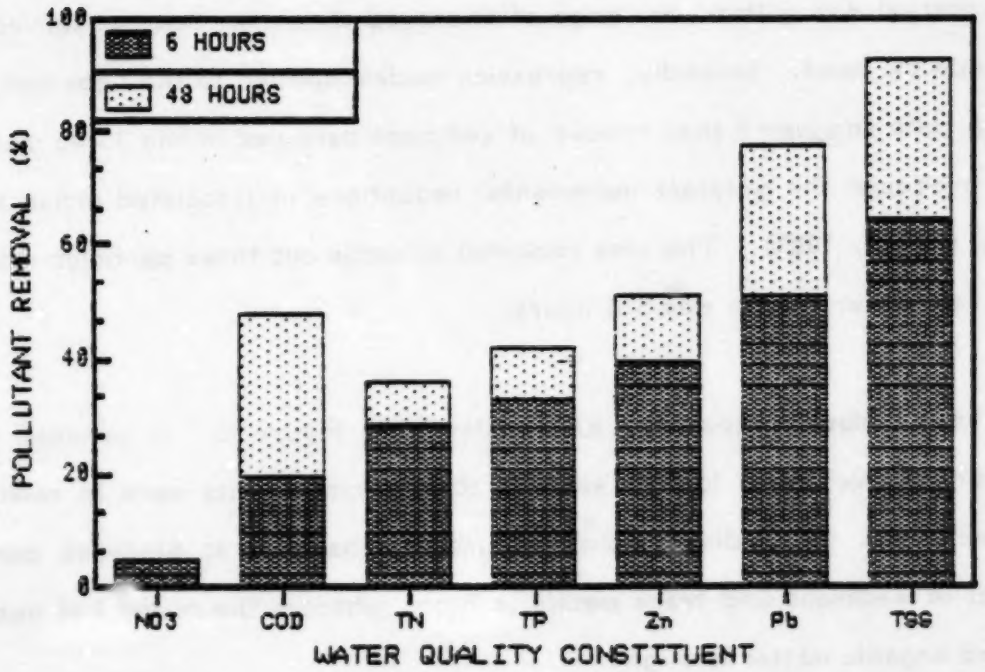


Figure 12

Removal Rates Observed in Experimental Settling Column Studies: Removal After 6 and 48 Hours



residential and commercial sites monitored in the NURP study. The objective of this analysis was to characterize the removal rate which might be expected for the median urban stormwater runoff event. As a check, these experimental removal rates were compared to the median load removal rates observed at the Stedwick extended detention pond.

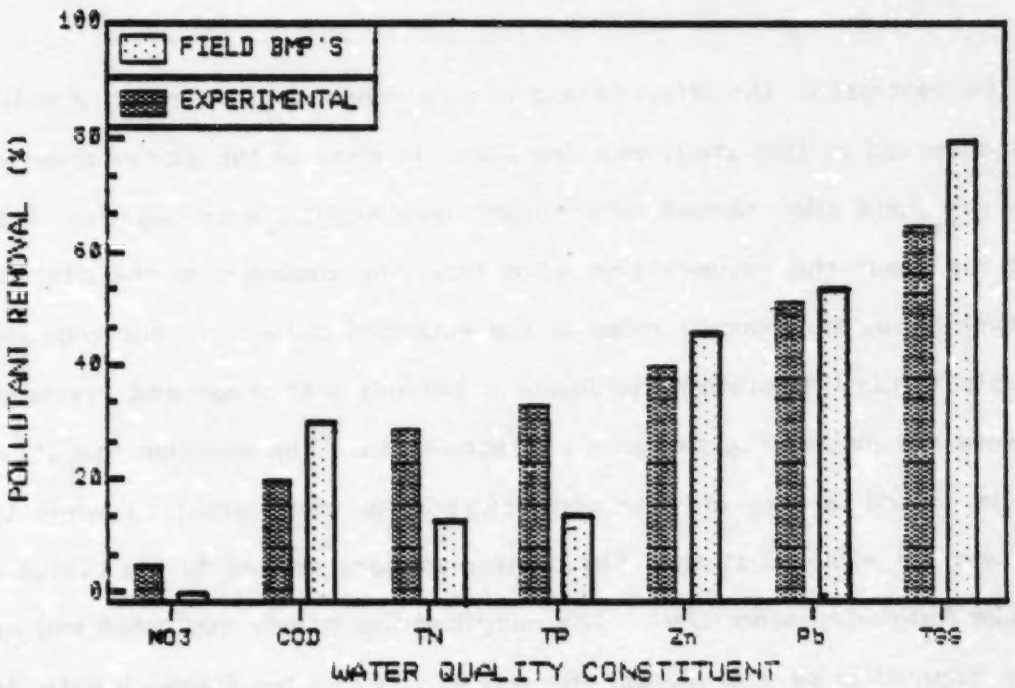
The stormwater concentration in settling column experiments which most closely approximated the NURP median urban runoff concentration was identified and the removal rate in that replication after six hours was determined. The six hour settling rate was fortuitious for two reasons. First, the six hour interval was within the range of observed detention times observed at the Stedwick pond. Secondly, regression models applied to the experimental settling data suggested that removal of sediment particles in the 35-45 micron range produced the greatest incremental reductions in associated urban pollutants (OWML, 1983). The time required to settle out these particles within a four foot water column was 5.6 hours.

These removal comparisons are illustrated in Figure 13. In general, the six hour removal rates for the settling column experiments were in relative agreement with the median loading reductions observed at Stedwick pond. Removal of sediment and trace metals is high, whereas the removal of nutrients and organic matter is slight.

The pollutant settling rates depicted in Figure 12 are most instructive. First, there appears to be an upper limit on the amount of removal that can be achieved by settling. In most cases, the greatest proportion of the removal occurs in the first six hours and then declines gradually thereafter. After 12 to 24 hours little, if any, additional removal takes place and a maximum removal threshold is reached. For sediment, this upper threshold of removal is approximately 90 percent. By way of contrast, the maximum re-

Figure 13

Comparison of Pollutant Removal Rates:Experimental and Field Measurements of Extended Detention: Median Storms, Approx. 6 hours



a. rates derived from six hour data in "Sediment and Particle Size Association Studies", Chapter 11, of OWML (1983)

b. The median storm was defined the runoff sample used in the settling study which most closely approximated to the median EMC recorded for all residential and commercial sites in the NURP study. This storm (#4) was identical for all quality constituents.

c. Median loading rate reduction observed in the Stedwick Extended Detention Pond, average detention time 4-8 hours.

moval rate for total nitrogen and phosphorus after 48 hours is only 40 percent. Even a smaller rate is observed for nitrate (10 percent). For COD, the maximum removal after 48 hours approaches 50 percent; while for trace metals the upper threshold of removal is about 50-80 percent. The conclusion which emerges is that if control of nutrient enrichment or oxygen demanding materials is a primary management objective, then other stormwater design features other than extended detention will be required.

2. Design of Dry Pond Beds

The contrast in the effectiveness of dry ponds and extended detention ponds observed in this study was dramatic. In many of the storms observed at the dry pond site, removal efficiencies were negligible or negative, indicating the scour and resuspension were recurring problems at the site. On the other hand, the removal rates at the extended detention pond compared favorably to ideal theoretical conditions, implying that scour and resuspension were not influencing the pond's effectiveness. The question that inevitably is raised is why did one pond experience these problems while the other was not affected at all. The answer appears related to the design of the Lake Ridge dry pond itself. The pond bed was poorly vegetated and was visibly scoured in several places. By way of contrast the Stedwick extended detention pond had: 1) extensive vegetation; 2) a narrow concrete channel leading into and through the pond; 3) energy dissipating structures which reduced water velocities at the inlet of the pond; 4) a tall riser with a gravel jacket which minimized the likelihood of resuspension of previously deposited materials; and 5) a pond configuration with a high length to width ratio which created ideal settling conditions and avoided problems of "short-circuiting" runoff storage. Incorporation of these design measures is recommended as a means of reducing the potential for detention basins to become a source of nonpoint pollutants.

3. Rapid Infiltration/Prolonged Contact Time

Although the performance of infiltration BMPs which were monitored in the NURP study was mixed, a closer scrutiny of the data individual structures and site conditions suggests that infiltration controls can be extremely effective if they are oriented toward: 1) achieving rapid and complete infiltration of stormwater, and 2) maximizing the contact time of stormwater within the soil.

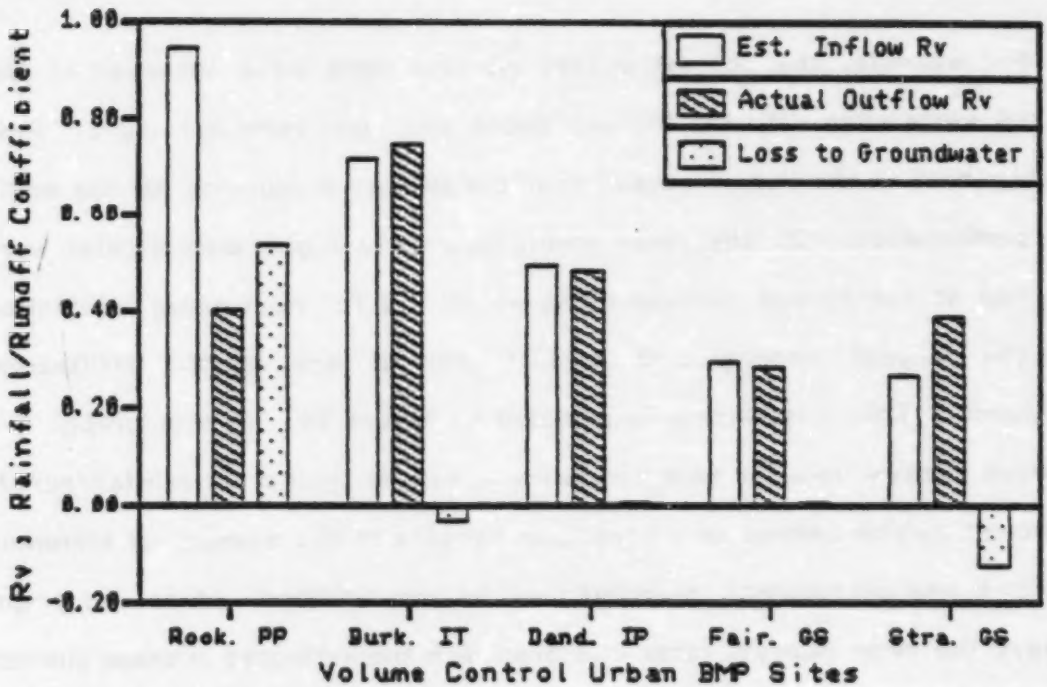
For example, the poorest overall removal rates were observed at the grassed swale sites with the highest slopes and least permeable soils. Presumably most of the runoff passed over the swales, accounting for the mediocre performance. On the other hand, extremely high removal rates were observed at the porous pavement site which had the most rapid infiltration and the largest underground contact time of any of the infiltration structures. This relationship is depicted in Figure 14. In this graph, the pollutant removal rate for each structure is plotted against its rainfall/runoff coefficient (which serves as a surrogate measure of the quantity of stormwater which was permanently diverted into the groundwater). A second graph displays the same removal rates compared with the estimated average contact time achieved within the structure itself (Figure 15).

4. Biological Removal by Pond Ecosystems

Figure 16 presents the comparative pollutant removal efficiencies which were observed in the dry pond and pooled wet ponds monitored in the NURP study. As can be seen, the removal rates are significantly higher for most parameters in the wet ponds. Of particular interest is the high removal of soluble nutrient forms which are often responsible for creating eutrophic conditions. While the removal of particulate substances is comparable to

Figure 14

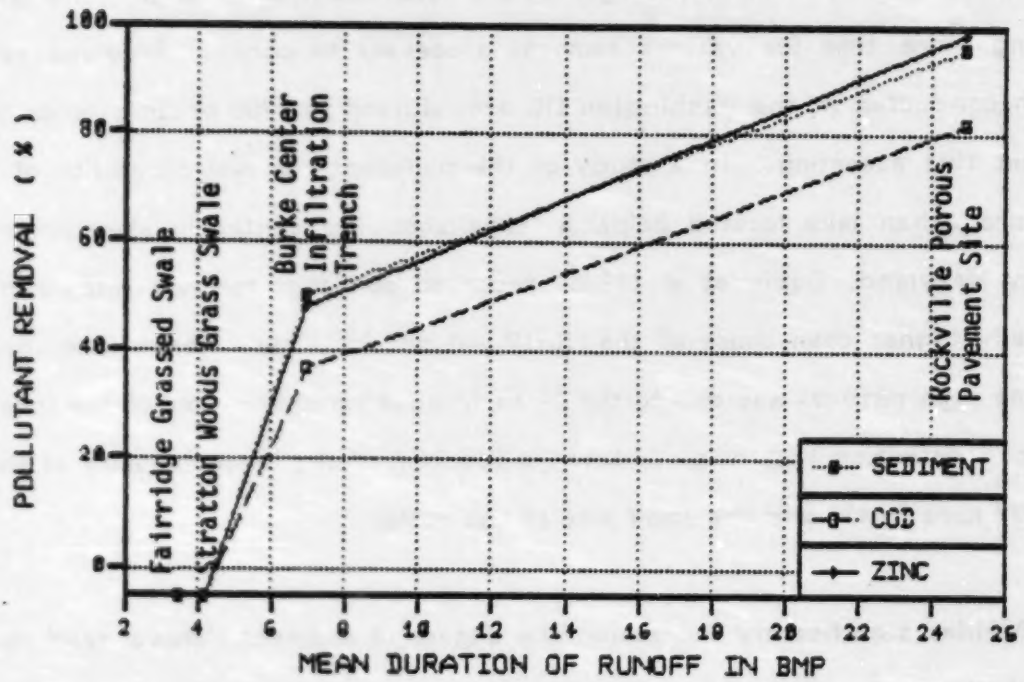
Estimated Diversions to Groundwater in Volume Control BMP's in the Washington Area NURP Study



Notes: Estimated Inflow Rv values were derived from functional relationships between imperviousness and runoff contained in preliminary assessment of the National NURP data base supplied by E.D. Driscoll and Associates. Actual Outflow Rv values were determined from on-site comparisons of rainfall and runoff volumes at each BMP site for at least 15 storm runoff events. Inflow Rv - Outflow Rv provides a surrogate measure of the proportion of incoming inflow which was diverted to the groundwater, (as opposed to surface runoff). As can be seen, only the Rockville Porous Pavement BMP site experienced these losses. The remainder of the volume control sites had equivalent inflow and outflow water balances.

Figure 15

Relationship Between Median Removal Rates and Mean Duration of Runoff in Volume-Control BMP Structures for Particulate Urban Pollutants



Note: Mean Duration of Runoff in BMP was defined and Calculated as the average time elapsed between the activation of the on-site rainfall gage and the termination of the outflow sampling monitor, less seven hours. (The seven hours represents the mean storm duration in the Northeast - 6 hrs (Driscoll, 1983) and a 1 hour interval of time of concentration. Removal estimates are based on the application of Method B (median loading rate efficiency) and should be interpreted in the light of previously mentioned limitations in characterizing inflow runoff loads. Any removal efficiencies below zero indicate negative efficiency only. Actual values were not supplied for clarity's sake.

those achieved at the Stedwick extended detention Pond (Figure 7), indicating that gravity sedimentation alone can account for most of the particulate removal, this additional removal of soluble nutrients is especially noteworthy. The principal removal mechanisms involved appeared to be nutrient uptake by phytoplankton and rooted aquatic vegetation.

The effectiveness of wet ponds appears to be related to the size of the permanent wet storage. Preliminary data of Driscoll (1983) suggest that removal efficiencies increase as pond areas increase (expressed as a percent of the contributing catchment area - Figure 17). This phenomena can probably be attributed to the fact that larger ponds retain pollutants longer, thereby allowing more time for various removal processes to occur. Previous research conducted in the Washington DC area during the 208 process tends to support this assertion. In a study of the pollutant removal capability of a six acre urban lake located below a large shopping center in Montgomery County Maryland, Davis et al (1978) reported pollutant removal rates substantially higher than those of the NURP wet ponds. The authors concluded that the high removal was due to the 24 to 72 hour detention time of the lake. The long detention time was, in turn, a function of the large capacity of the lake (37 acre feet), and the small size of the outlet.

Besides significantly increasing the degree of nutrient removal from runoff which can be achieved, wet ponds also serve other important purposes. For example, a recent survey of 360 residents in Columbia, Md. (Table 16) suggests that the public considers wet ponds to be important resources with respect to wildlife attraction, landscaping, aesthetics, recreation and property values (Adams et al, 1983). A distinct preference for living adjacent to wet ponds rather than dry ponds was also exhibited in this survey. The multi-purpose character of wet ponds, when coupled with their high pollutant removal capabilities suggests that they should be more fully utilized as a

Figure 16

Comparative Performance of Wet and Dry Stormwater Management Ponds in the Washington Area NURP Project

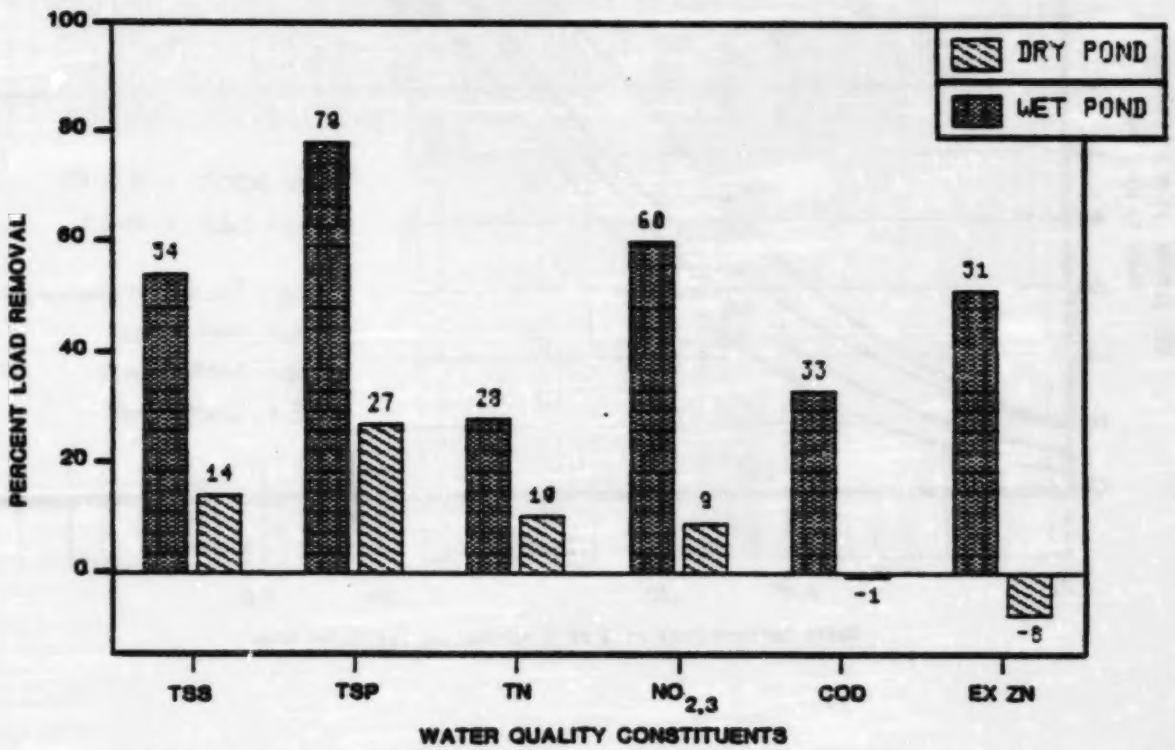


Figure 17

Effect of Pond Area on Long Term
Pollutant Removal Efficiency

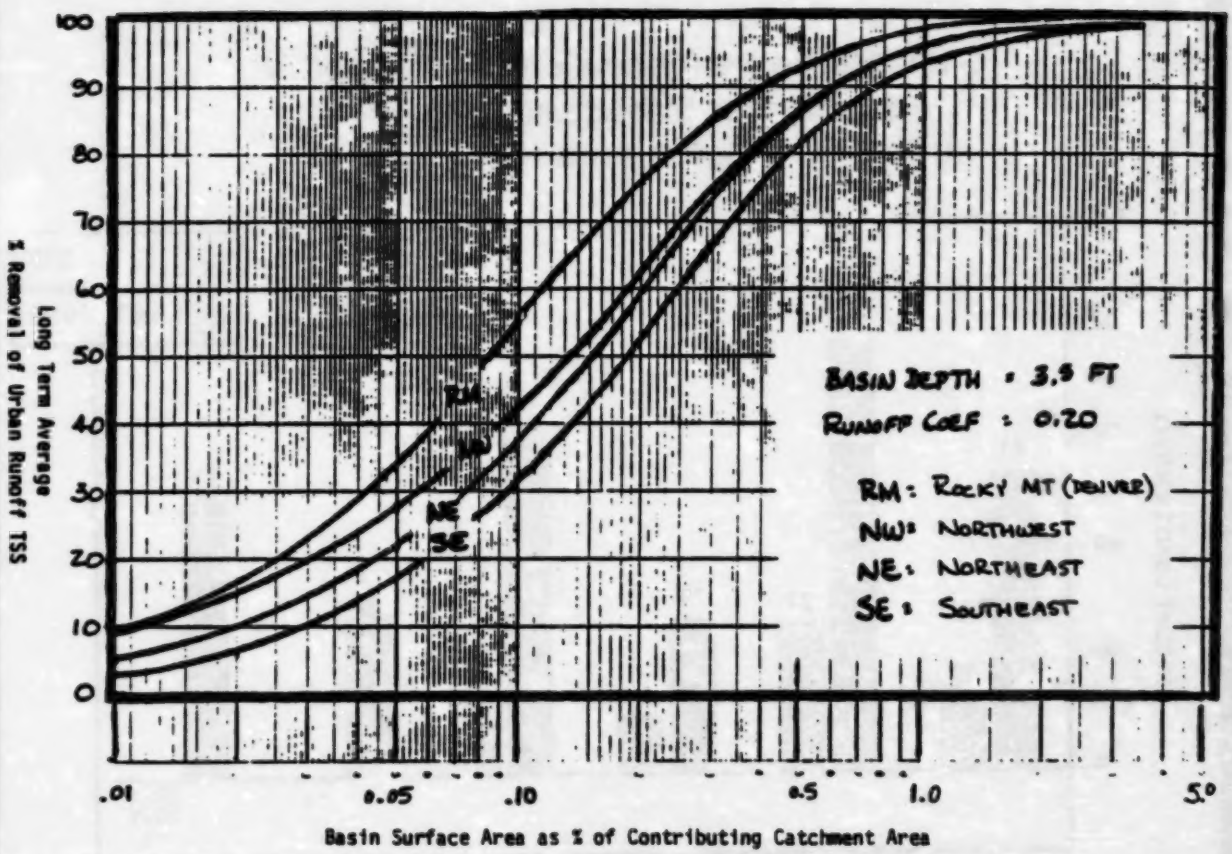


Table 16

Citizen's Attitudes Towards Stormwater Basins

94% of residents felt it is desirable to design and manage stormwater basins for fish and wildlife

Residents prefered wet ponds over dry ponds by a 4 to 1 margin

75% of residents felt wet ponds add to the real estate value of their homes

73% expressed a willingness to pay more for home situated near a wet pond

Residents perceived benefits of ponds:

	Wet (%)	Dry (%)
Wildlife attraction	65	22
Aesthetic appeal	58	22
Recreation opportunity	40	5
Fishing	29	0

Source: National Institute for Urban Wildlife Resident Attitude Survey, Columbia, MD. 360 Respondents

stormwater management strategy, rather than relying on the more limited benefits expected from conventional dry ponds.

Additional Comments Regarding BMP Efficiency

One of the most fundamental conclusions reached during the Washington area urban BMP effectiveness study is that the pollutant removal behavior of any urban stormwater management practice is extremely complex and variable. While many clearly defined trends were evident in the Washington area database, it is worth noting that each of the 14 BMP sites which were monitored operated in a unique manner, reflecting certain complex site-specific factors. The practical implication, then, is that many factors conspire to influence the pollutant removal behavior of a particular urban BMP, and that each of these factors have to be carefully scrutinized when designing and maintaining a structure to achieve optimal efficiencies. Some of these factors include: 1) the nature and characteristics of the upstream catchment area (e.g., drainage area, land use, soils, loading rates), 2) the quantity of stormwater generated during each storm and the concentration of entrained pollutants, 3) the design criteria of the BMP device (i.e., whether the device effectively regulates runoff from smaller storm events, as well as the 2, 5, 10 or 50 year design storm), 4) the size or storage capacity of the control device relative to its upstream catchment, 5) the actual performance of the device in the field (i.e., does the outlet become clogged, or leak, etc.), and 6) the level of maintenance performed on the BMP over its useful life.

Therefore, the influential effects of these and other factors on the pollutant removal capability of any BMP should be explicitly recognized in the BMP design and site review process.

SUMMARY: CONCLUSIONS AND RECOMMENDATIONS

Six kinds of stormwater management controls in use within the Washington Metropolitan area were analyzed to determine their effectiveness in removing pollutants borne in urban runoff. These structures included conventional dry stormwater ponds, extended detention dry ponds, wet stormwater ponds, grassed swales, infiltration trenches and porous pavements. Inflow and outflow from 12 BMP sites was monitored with automated sampling equipment for intervals of 12 to 18 months, and several different estimates of pollutant removal efficiency were computed. The general conclusions concerning the pollutant removal effectiveness of these stormwater controls are as follows:

- Conventional dry stormwater management ponds are not effective in removing the sediments, nutrients, trace metals, or oxygen demanding materials entrained in urban runoff. Stormwaters pass through the structure too quickly to achieve significant removal by settling. In some cases, dry ponds can actually become sources of pollutants if the pond bed is not stabilized.

- Extending the detention time of stormwater within dry ponds is a promising technique for removing several common constituents such as sediments, trace metals, and organic nutrients. Removal of biologically available nutrient forms, however, is minimal. This suggests that the extended detention technique will not be useful in areas where control of nutrients is a primary management concern.

- Wet ponds were determined to be an extremely effective urban best management practice. Removal rates for sediment and trace metals were comparable to those observed at the extended detention facility. Also, the biological processes occurring within the pond effectively removed a high proportion of the readily available nutrient forms.

- No statistically significant improvement in either runoff quality and quantity could be demonstrated for grassed swales, when they were compared to their traditional curb and gutter control. The poor performance of the grassed swales appears to be related to the rapid passage of stormwater through the swales.

- Although several methodological and siting constraints limited the usefulness of the infiltration control comparisons, it did appear that these controls tended to be moderately effective in removing sediments, trace metals and oxygen demanding materials, but were generally ineffective in removing soluble nutrient forms and oxygen demanding materials.

- The use of porous pavements proved to be a very effective urban best management with respect to both runoff quality and quantity. High removal rates were noted for nearly all water quality parameters.

During the course of the study, several design concepts emerged as having significant potential for enhancing the pollutant removal capability of stormwater structures. These concepts include:

- Increasing the detention time of stormwaters in pond structures. Evidence Evidence presented earlier suggest that 6 to 12 hours of detention is sufficient to achieve about two thirds of the maximum theoretical removal rate. Since removal rates beyond 12 hours occur only in small increments, (and the cost of adding additional storage remains constant) the achievement of extremely long detention times should be carefully examined.

- Pond scour, resuspension, and short-circuiting are all processes which can severely limit the pollutant removal capability of any pond BMP. Therefore, in the design process, special attention should be placed on preventive measures such as revegetation, bank stabilization, energy dissipation, channelization and pond configuration.

- Infiltration-type BMPs can be extremely effective if they are oriented toward achieving rapid and complete infiltration of stormwater and maximizing the contact time of stormwater within the soil profile. In this respect, infiltration systems should best be designed to retain stormwater within the structure for durations exceeding those suggested for ponds. Design retention times of 24 to 48 hours are frequently recommended because of the smaller storage and through-put of infiltration devices. (Wong, personal communication , September 27, 1983). Even greater performance can be realized if the stormwater is permanently routed into the groundwater pool.

- The multi-purpose character of wet ponds, when coupled with their high pollutant removal capability, strongly suggests that they can be an at-

tractive stormwater management strategy. In general, the pollutant removal efficiency (and presumably the aesthetic, recreational and landscape values, as well), will become greater as pond size increases. Also, the establishment of rooted aquatic vegetation around the periphery of the pond can accentuate pollutant removal as well as attract wildlife. Establishing rooted aquatic vegetation also may have the beneficial effect of diminishing the nutrient supply available to noxious algae during the summer months, thus alleviating a persistent maintenance concern.

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